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In most previous investigations of short-term visual memory (STVM), displayed material was restricted to alphanumeric items with well-learned names, and a naming response was required. The primary question ~~addressed by this research was the~~ addressed extent to which the processing of items with well-learned names differs from that of items without well-learned names. To address this question, a new paradigm was created that does not require items to have names and does not require a naming response. In many ~~STVM~~ paradigms, a bar marker designates a display location and the task is to name the item in that location. In the new paradigm the marker is replaced by a comparison item positioned above a display location. Instead of naming the item in the location, the subject's task is to say "yes" if the item in the indicated location is identical to the probe, and "no" otherwise.

Data were collected from six subjects in a large (75,000 trial) experiment. A multiple regression model was formulated and applied to these data to compensate for non-orthogonalities in the experimental design that could not be avoided. Several models of the processing underlying

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performance were also generated and tested. Regression and modeling results were then used in data analyses.

Analyses indicated that (1) changes in the underlying representations for forms with and without well-learned names take place; (2) these changes are qualitatively similar for the two kinds of material; and (3) the representation of items without well-learned names is searched more slowly than the representation for named items. Results ~~also~~ confirm the earlier findings of Sternberg and his associates (see Sternberg & Knoll, 1985; Sternberg, Knoll, & Turock, 1985; 1986; 1987a; 1987b) that (1) an item in STVM is accessible without search through other items only when onset asynchrony between probe and display is small, and (2) as the asynchrony between probe and display is increased, STVM undergoes an active transformation from a state that is accessible without search through items to one that must be serially searched. Keyword: Visual Image Memory.

TRANSFORMATION OF VISUAL MEMORY
REVEALED BY LATENCY
OF LOCATION-SPECIFIC MATCHING

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A dissertation submitted to the

Graduate School – New Brunswick

Rutgers University, The State University of New Jersey

in partial fulfillment of the requirements

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New Brunswick, New Jersey

May, 1988

1. Introduction

This thesis is concerned with the internal representation of visually displayed information and how it changes within the first two seconds after presentation. The primary question addressed is the extent to which the processing of forms with well-learned names differs from that of forms without well-learned names.

In the next section a review of the relevant research on short-term visual memory (STVM) is presented. It is evident that in much of this research two assumptions were made: (1) for all probe delays a spatially contiguous subset of one or more of the items in memory can be accessed without search through other items (the *direct access* property), and (2) the memory representation that is accessed is analogous to a "fading photograph" and is not actively changed by cognitive processing. Results from recent experiments are presented that indicate these assumptions are incorrect by demonstrating that (1) under certain circumstances STVM *must* be actively searched, and (2) STVM undergoes an active transformation, rather than passively decaying.

In sections 3.1 to 3.4, two limitations in the experimental paradigms used in previous research are identified: (1) displayed material was restricted to alphanumeric items with well-learned names, and (2) a naming response was required. A new paradigm is then described that does not require items in memory to have names or be named as a part of the response. Several advantages of the new procedure are then discussed. In addition to providing an experimental tool for investigating the differences between items with and without well-learned names, it is shown that the new procedure: (1) provides a test of the direct access property; (2) provides a test of whether the processing of items in memory other than the one marked for recall influences reaction time (RT) in any way; (3) can be used to demonstrate that the effects observed in earlier work by Sternberg & Knoll (1985) are due to changes in the memory representation, and not changes in the size of the response set; (4) allows a test of whether changes in the height of the function relating the number of items in memory to the RT to name a single item is related to the generation of an internal name code; and (5) provides a test of the Posner, Boies, Eichelman, and Taylor (1967) hypothesis that early representations are visual, while later representations are analogous to names.

Aspects of experimental design and procedure are presented in Section 3.5. The experimental manipulations include both naming and matching tasks and, in the matching tasks, using stimulus items with and without well-learned names.

Results are discussed in sections 3.6.1 to 3.6.13. A multiple regression model used to statistically correct for unavoidable non-orthogonalities in the design and for the unwanted effects of factors such as retinal eccentricity is first described, along with a procedure for converting the output of the regression into fitted RT measures. Four quantitative models of the transformation and retrieval processes underlying performance are then presented. The first postulates a search through a set of locations, followed by a search through a set of identities; the second assumes a search through a set of identities, followed by a search through a set of locations; the third and fourth assume a simultaneous search through location and identity information. Patterns in fitted RT lead to the rejection of all of these models.

Fitted RT's are then used to study patterns in the data. It is concluded that a transformation occurs for items with and without well-learned names, but that the representation for the latter is searched more slowly. Results from other analyses suggest that: (1) the direct access property is present for short probe delays, but disappears for long delays; (2) the effect of processing the content of other filled display locations is negligible for some conditions; (3) results of Sternberg & Knoll (1985) are not due to changes in the size of the potential response set; (4) there may be no simple relation between parameters of the latency function and the availability of names of memory items; (5) the expectation based on the Posner et al. (1967) hypothesis is not in evidence.

In Section Four, the thesis concludes with a summary of the principal findings; Section Five presents ideas for future research.

2. Previous Research

In this section, some of the previous research relevant to the questions addressed by the thesis is summarized and discussed. For over a century, psychologists have known that when a display containing from 10 to 20 letters or digits is presented to a subject for less than 500 ms they can report only about four items correctly. Sperling (1960) demonstrated that the factor limiting performance in this "whole-report" task is not the apprehension of items in the display, but memory for the items: if 12 display items are grouped into three rows of four, and a tone indicating which row is to be reported comes on after the offset of the display, the average number of items that can be recalled is three. Since subjects have no knowledge of which row is to be reported before the offset of the display in this tone-cueing "partial-report" procedure, Sperling inferred the number of items stored in memory is about nine. He also noted that as the time between display offset and tone increases, the number of items that can be correctly reported decreases until the partial-report provides no advantage over whole-report. He interpreted these results as indicative of a high-capacity rapidly decaying memory.

In another study, Averbach & Coriell (1961) presented subjects with displays of 16 alphabetic characters followed by a visual probe marking one location in the display. The subject's task was to report the item that had been in the marked location. Short-delay probes resulted in estimates of storage capacity of about 10 to 12 items; as probe delay increased, estimates of capacity gradually decreased to about four items. Like Sperling, Averbach & Coriell interpreted their results as indicative of a rapidly decaying memory.

Two assumptions were made in interpreting these experiments: (1) for all probe delays a spatially contiguous subset of the items in memory can be accessed directly (without search through other items) and (2) the memory representation that is accessed is analogous to a "fading photograph" and is not actively changed by other processes. Lately these assumptions have come under question. New results have emerged that cannot be parsimoniously explained without postulating the existence of active search mechanisms, and a qualitative change in the representation other than "fading". (See, for example, Haber, 1983; Mewhort, 1982; Mewhort, Campbell, Marchetti & Campbell, 1981; Coltheart, 1980; Mewhort & Campbell, 1978; Turvey, 1978; Dick, 1971; Davidson, Fox & Dick, 1973; Mewhort & Merikle, 1969; Mewhort, 1967.)

Most research on short-term visual memory (STVM), including that of Sperling, and Averbach & Coriell, used accuracy as the primary dependent variable and hypothesized that the only form of transformation of the internal representation was passive degradation or "decay". Results from other research suggest that this assumption may be incorrect. For example, in another type of paradigm using RT as the primary variable, Posner, Boies, Eichelman, and Taylor (1967) found evidence for an active transformation rather than merely progressive degradation. Posner et al. presented subjects with two letters in temporal succession and asked them to respond "same" if the letters had the same name, and "different" otherwise. Results indicated the latency to respond "same" to a physically identical pair of letters (e.g., AA) is less than that required if the pair of letters are identical in name only (e.g., Aa); this difference decreases with increasing onset asynchrony between the two letters. Posner et al. interpreted this finding to mean that when stimuli are physically identical, short intervals between letter onsets allow rapid comparison between visual representations; after some delay this visual representation is transformed into one based on a name code, and these codes are compared. Unfortunately, this interpretation was not totally without difficulty: Posner et al. also claimed that other aspects of their data showed that a visual code could be generated from a name representation.

Sternberg & Knoll (1985) have developed another reaction-time technique for studying the internal representation of a display and how information is retrieved from it. Since high accuracy is important in the straightforward interpretation of RT data, subjects are presented with small displays, typically a single row of from two to six digits. Similar to the Averbach & Coriell procedure, at various delays relative to the onset of the display a probe that takes the form of a visual marker indicates the location of one displayed item. The subject's task is to name the probed item as rapidly as possible. There are four main advantages of this "Location-Probe" (LP) paradigm over the techniques used by most researchers. The first lies in the utility of using reaction time measures in lieu of error frequencies: unlike procedures in which the primary measure is accuracy and the goal is to determine the *presence* of information in memory, performance in this paradigm is sensitive to the *accessibility* of information that is present — the speed with which such information can be retrieved. The second advantage is that patterns of RT may change systematically —and thus allow study of the underlying processing— while accuracy remains the same. The third is that variations in array size permit assessment of the magnitude of the array-size effect. This allows more detailed study of that subset of the processes associated with searching the memory representation. The fourth is that the procedure allows conditions where the display is prolonged to be studied.

Data from the Sternberg & Knoll paradigm reveal several important facts about retrieval of information from initial and subsequent memory representations. First, the functions relating latency to the number of items in the display are approximately linear for all probe delays examined from -350 ms (i.e., the probe comes on before the display) to delays of over three seconds. Second, the slopes of these "latency functions" are close to zero for negative and small positive delays, and increase monotonically up to delays of between 0.6 and 1.0 second, after which they remain relatively constant. Third, as the slopes of the functions increase, their intercepts decrease. The fact that slope and intercept change in opposite directions with increases in probe delay demonstrates the *necessity* of studying more than one array size. Data from a single array size (e.g., two) indicates performance improves with increasing probe delay; data from array-size six indicates performance declines. Conclusions drawn from the study of a single array size may thus be misleading. This relationship is depicted in Figure 1, in which slope and one-intercept[1] are plotted for a subset of the probe delays studied by Sternberg & Knoll.[2]

1. A justification for the study of one-intercepts is presented in Section 3.6.5.

2. For conditions where probe onset precedes that of the array, it is not clear where to start the clock that measures RT so that times for these conditions are comparable to conditions where array onset precedes that of the probe. It is thus not appropriate to consider intercepts from negative probe delay conditions on the same scale as those from positive delay conditions. The data point for the intercept at the -50 ms probe delay is thus omitted in this figure.

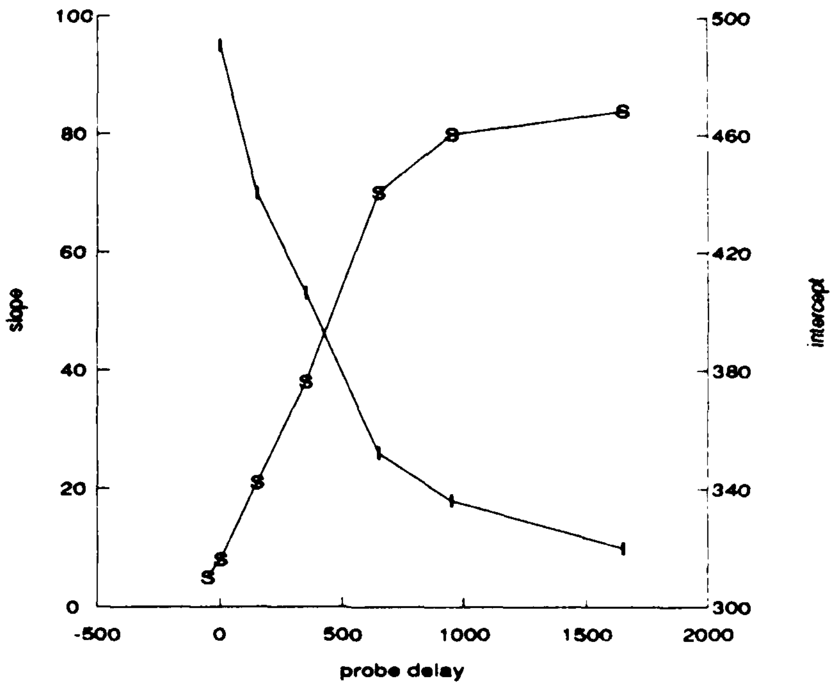

Figure 1. Effect of Probe Delay on Slope and One-Intercept

Sternberg & Knoll interpret changes in slope as follows: The initial flatness of the functions suggests the existence of a representation from which an item in a particular location can be addressed directly, without search through other items in the display. The rapid increase in slope indicates the initial representation is rapidly transformed into one that requires search: even after a short delay, reaction time increases with the number of items in the displayed array. The initial presence of the direct access property confirms the assumption of its existence made in the error studies; its disappearance with delay, however, casts doubt on the validity of the assumption made in these studies that direct access is possible at all probe delays. The fact that RT is reduced with increasing delay for some array sizes also provides evidence for a transformed representation, rather than one that simply decays. The fact that the latency function is linear at all delays suggests that the same process applies to all array sizes in the range examined. Under these conditions, the traditional view of a memory representation analogous to a fading photograph is questionable.

Changes in intercept, according to Sternberg & Knoll (1985), may indicate that names of items are changing in availability. As the transformation progresses, the internal representation of an item changes in such a way that once it is retrieved its name can be derived from it more rapidly. The time to determine the name of an item from its representation thus depends on the state of the representation. If it is only partially transformed, or if its probability of having been transformed is low, more processing is required to generate a name before a vocalization can occur; the mean processing time required decreases with increasing amounts of (or probability of) transformation. The time required to generate a name for an item is thus a function of probe delay.

The Sternberg & Knoll results and interpretations are strengthened by data they have collected in two similar paradigms they have named "Identity-Probe" (Sternberg, Knoll, & Leuin, 1975), and "Probed-Reciting" (Sternberg & Knoll, 1985). In the first, the probe is the spoken name of one of the items in the array. The subject's task is to name the item in the array to the right of the probe. In the second, the probe is one of two tones. The subject responds to one tone by reciting the entire array in a forward (i.e., left to right) direction, and to the second by reciting the array backwards. Data from both paradigms lead to similar conclusions regarding the existence and time course of a transformation.

3. New Research

3.1 Location-Specific Matching Procedure for Assessing the Representation of Arrays in Memory

In the LP paradigm a visual marker —a vertical line above and below a single location in the display— is used to indicate the item to be retrieved from a linear array of items. To provide a tool for investigating the research questions of the thesis, a new paradigm for assessing the internal memory representations of arrays, called Location-Specific Matching (LSM), was developed. In the new paradigm, the visual marker of the LP paradigm is replaced by a comparison item above a display location. Instead of naming the item in the location, the subject's task is to say "yes" if the item in the indicated location is identical to the probe, and "no" otherwise.

3.2 Benefits of the LSM Procedure

There are three principal advantages of the new procedure. First, it allows detailed study of the nature of any transformation that occurs when the items in memory have well-learned names but need not be overtly named to perform the task. Second, it provides a tool to study any transformation that occurs for nameless memory items. Third, given the existence of a transformation for the two types of items, similarities and differences between the transformation processes for each type of item can be assessed within the same experimental procedure.

3.3 Primary Research Focus: Dependence of the Transformation Process on the Need to Name Items in Visual Memory

Two significant limitations of previous work are that in most studies (1) displayed material was restricted to alphanumeric items with well-learned names, and (2) a naming response was always required.[3] The transformation may depend qualitatively and/or quantitatively on items having readily available names and on these names having to be produced to perform the task. For example, the end result of the transformation of an array when the ultimate response is overt naming might consist of a sequence of covertly produced names. Two important questions arise: First, if stimuli have well-learned names but the experimental task calls for a response that doesn't require items to be named, does the same transformation take place? Second, is there evidence for a transformation when stimuli consist of nameless[4] items? If so, in what ways is this transformation similar to the one for nameable items, and in what ways is it different? The answers to these questions are important in understanding mechanisms of visual processing.

3.4 Secondary Focus: Tests of Inferences and Assumptions Made in Previous Work

The LSM paradigm also provides a way to test several inferences and assumptions made in previous research on STVM.

3.4.1 Direct Access by Spatial Location

Whether access is *direct* is a fundamental characteristic of *any* memory. As discussed, in the context of STVM the presence of direct access means that no search or time consuming process involving other display locations or their contents is needed to gain access to information in a suitably specified display location. Direct access is violated when, with non-zero probability, other filled locations are processed before the specified location. The extent of directness is a key issue in understanding the basic mechanisms of visual processing. Further, much of the work reported in the STVM literature assumes the direct access property is present at all probe delays. Data from the LP paradigm bring this assumption into serious question.

3. One of the few exceptions is research by Phillips (1974) and Phillips & Baddeley (1971) who studied how single-item arrays of dot-matrix figures change over time.

4. In the context of this thesis, "nameless" means only that elements do not have well-learned associations with names, as do alphanumeric characters.

In the LSM procedure flat latency functions would indicate the direct access property, as in the LP paradigm.[5] The procedure thus provides a way of testing for direct access and an opportunity to extend the finding from the LP paradigm that direct access by spatial position is present only for the initial representation of a visual array. If this conclusion is correct, functions should be flat for short probe delays only; longer delays should result in steeper functions.

3.4.2 Selective Access

Another defining characteristic of a memory is whether or not it can be *selectively* accessed. For STVM, "selective access" describes situations in which direct access may or may not be present, but the *contents* of display locations (i.e., the identities of items) other than the one probed are not processed in any way. Selective access is violated when, with non-zero probability, the contents of locations other than the one probed influence processing of the probed item. Experiments to investigate selectivity typically present a display containing a target item among either (1) no distractor characters, (2) distractors with the same name and form as the target (e.g., T and T), or (3) distractors differing from the target in name and/or form (e.g., T and t, or T and F). The typical result relative to the control (1) condition is a facilitation in RT for condition (2), and interference in condition (3). Using different variations on this general technique researchers have found effects of the number of non-target items in the display (Eriksen & Spencer, 1969); contrast and size differences between distractor and target items (Eriksen & Shultz, 1979); and the distance of distractor items from the target (O'Hara, 1977; Gatti & Egeth, 1978). Eriksen & Eriksen (1974) concluded the minimum size of the processing field is about one degree of visual angle. Thus, the current body of literature suggests that selectivity in display processing tasks is limited.

In the LSM procedure, the target item can be present in the displayed array in a location other than the one probed. These *out*-of-location targets provide a test for selectivity of access. If a representation is selectively accessed, then the content of locations other than the one probed should not be processed. Hence, out-of-location targets should neither facilitate or inhibit a "no" response. Conversely, if selectivity fails, differences should be observed between trials where the target item is not present in the display, and trials where it is present, but not in the probed location.[6]

3.4.3 Effects of Response Ensemble

One possible explanation of the observed patterns in slope and intercept in the Location-Probe paradigm is that for short probe delays subjects do not have time to prepare selectively for the set of possible responses while, with longer delays, they have time to activate some responses (since they know the probed item will have to be among those in the display), and discard others. Thus, as probe delay increases, responses for arrays with few items will be facilitated to a greater degree than responses for larger arrays. The LSM procedure provides a test of this "response ensemble" interpretation of the effect of array size: if the effects observed in the LP studies were due to response ensemble, these effects should not be manifested in the new procedure since the possible responses ("yes", "no") are the same regardless of array size, and are known before the array is displayed.

3.4.4 Changes in Intercept and the Availability of Names

Another important question concerns the conjecture that changes in intercept in the Location-Probe paradigm are a consequence of changes in the underlying representation such that names can be derived faster from later representations. Since the LSM procedure does not require a naming response, it is possible that no covert naming will take place. The observation of little or no intercept change when the LSM procedure is used with either named or nameless stimulus items would thus support the conjecture that decreases in intercept indicate a representation from which names are more readily generated.

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5. This measure of direct access relies on the implicit assumption that either empty display locations are not processed, or their processing adds less to RT than processing of filled locations when direct access is violated.

6. This argument assumes that if adjacent locations have content (rather than being empty), this will increase RT, given the failure of selective access.

3.4.5 Feature vs Name Matching Hypothesis

Posner et al. (1967) conclude that the decreasing RT difference between mean match RTs observed with increasing onset asynchrony between pairs of physically identical versus nominally identical but physically different letters is due to the fact that a small onset asynchrony leads to comparison between visual representations while a long asynchrony forces visual representations to be transformed into name codes, which are then compared. On trials with array size equal to one, the LSM paradigm is similar to that used by Posner et al. (1967). Consequently, the LSM procedure allows a test of the Posner et al. conclusion. Since items do not require naming, comparisons may be made between stimuli with and without well-learned names. If the Posner et al. interpretation is correct, it is possible that RT for stimuli with well-learned names will increase with increases in probe delay, while RT for nameless stimuli will remain the same.

3.5 Method and Design

3.5.1 Subjects

Six women, ages 38 to 50, from the Murray Hill, New Jersey community were each paid $256 for 47 hours of participation over a three month period. All had prior experience with tachistoscopic displays.

3.5.2 Apparatus

A real-time computer outfitted with auxiliary hardware controlled all aspects of the experimental procedure, including the presentation of displays and the collection of vocal response latencies. Displayed items, drawn using a Megatek vector display generator, were light on a dark background and presented on a Hewlett-Packard Model 1311A cathode ray tube (CRT) oscilloscope equipped with Hewlett-Packard P4 rapid decay phosphor. Displays were refreshed once every three ms. The Luminous Directional Energy (LDE) per item (see Sperling, 1971) was 0.38 ftL. Measurement of the dark (background) area of the display scope indicated a luminance of 0.01 ftL.

3.5.3 Organization of Experimental Conditions

Table 1 summarizes the organization of the experimental conditions. Left-to-right ordering of paradigms and delays coincides with the temporal order in which subjects were tested.

Paradigm: LP - Location Probe MD - Match Digits MN - Match Nameless
Probe Delays: -50, 350, 650, 950, 1650

Cycle 1, 3, 5			
Subject		Paradigm and Probe Delay	
1	LP(-50,950)	MD(650,950,350,1650,-50)	MN(950,650,1650,350,-50)
2	MD(950,-50,350,650,1650)	LP(-50,950)	MN(-50,950,650,350,1650)
3	MN(-50,1650,350,950,650)	LP(950,-50)	MD(1650,-50,950,350,650)
4	LP(-50,950)	MN(350,-50,650,1650,950)	MD(-50,350,1650,650,950)
5	MN(650,350,950,-50,1650)	MD(350,650,-50,950,1650)	LP(950,-50)
6	MD(950,1650,650,-50,350)	MN(1650,950,-50,650,350)	LP(-50,950)

Cycle 2, 4, 6			
Subject		Paradigm and Probe Delay	
1	MN(-50,350,1650,650,950)	MD(-50,1650,350,950,650)	LP(950,-50)
2	MN(1650,350,650,950,-50)	LP(950,-50)	MD(1650,650,350,-50,950)
3	MD(650,350,950,-50,1650)	LP(-50,950)	MN(650,950,350,1650,-50)
4	MD(950,650,1650,350,-50)	MN(950,1650,650,-50,350)	LP(950,-50)
5	LP(-50,950)	MD(1650,950,-50,650,350)	MN(1650,-50,950,350,650)
6	LP(950,-50)	MN(350,650,-50,950,1650)	MD(350,-50,650,1650,950)

Table 1. Ordering of Conditions and Probe Delays

Subjects were tested in three paradigms, Location Probe (LP), Location-Specific Matching with digit stimuli (Matching Digits or "MD"), and Location-Specific Matching with nameless shapes (Matching Nameless or "MN"). Each repetition of a group of three paradigms (LP, MD, MN) constituted a *cycle*: there were six cycles in the experiment. To balance over linear trends, ordering of paradigm and probe delay within a cycle was designated by rows of a Latin Square.

For the LP task, subjects were tested at two probe delays, -50 and 950. These delays were chosen so that comparisons could be made between data obtained in this experiment and data from earlier work (e.g., Sternberg, Knoll, & Turock, 1985). To allow direct comparisons between the MD and MN paradigms, the same five delays were studied for each, -50, 350, 650, 950, and 1650. Across subjects, ordering of probe delays within each of the MD and MN paradigms was also designated by a complete Latin Square. Subjects were tested at two probe delays per day.

3.5.4 Stimulus Materials

Several aspects of the stimulus materials were identical for the three paradigms. The number of items in the array ("array size") was balanced over trials, as was the position of the probe relative to the first item in the array ("relative position"), and the absolute position of the probe within the display region ("absolute position"). The display region contained a row of equally-spaced locations large enough to accommodate the largest array size used for a given task. Displayed arrays occupied contiguous subsets of these locations. Each array item subtended 0.5 degrees of visual angle vertically, and 0.4 degrees horizontally. Center to center distance between items was 0.8 degrees.

Aspects not common to all three paradigms included the type of stimulus, maximum array size, and type of response. In the LP and MD paradigms, the digits 0 through 9 comprised the stimuli; array size was varied from one to five elements. Figure 2 depicts the stimulus forms used in the MN paradigm.[7]

7. Note that some of these forms are transformationally related. These relations were introduced so as to make it even less likely that subjects would associate names with any of the forms.

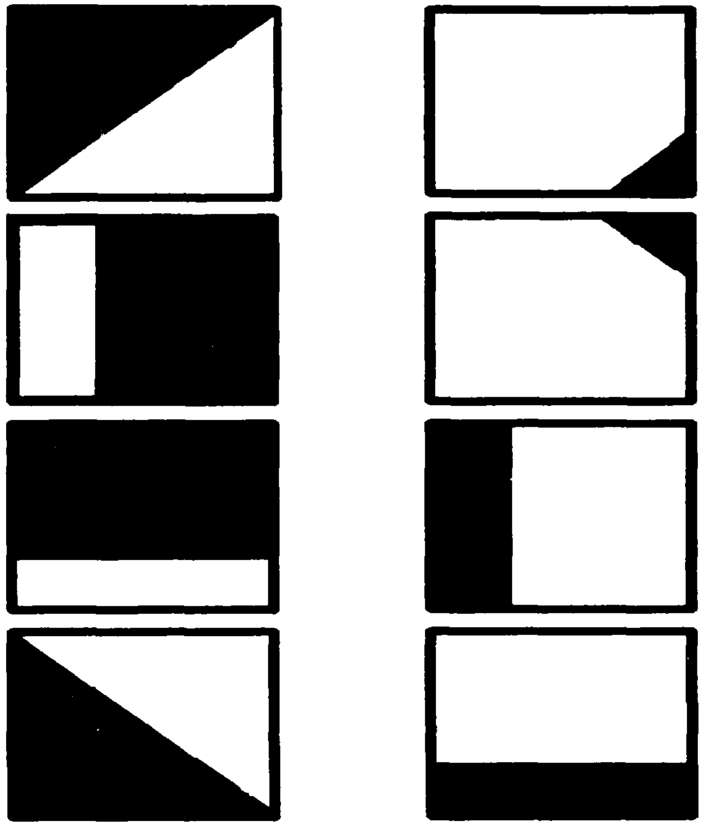

Figure 2. Nameless Forms used in MN Paradigm

To keep error rates low, and because inclusion of a very difficult condition might influence a subject's strategy in performing the task in other conditions, only array-sizes one through four were used in the MN paradigm.

For both matching paradigms, responses were balanced 50% "yes", 50% "no" within each array size. For array-sizes greater than one, there were two kinds of "no" trials. On half of these trials, the target item was present in a location adjacent to the one specified by the probe ("no/in" trials). (Whether the target was to the left or right of the probed item was decided randomly unless the leftmost or rightmost element of the array was to be probed.) On the other half, the target item did not appear in the array ("no/out" trials).

3.5.5 Procedure

At the beginning of each session, subjects were informed of the paradigm and probe delay they were to be tested in, and reminded to respond as rapidly as possible, consistent with making no more than one or two errors per block.

A brief (120 ms) pink noise burst signaled the onset of each trial and was followed 380 ms later by two vertical fixation lines, one above and one below the center of the display. Subjects were then given 1300 ms to focus their attention, fixate, and accommodate. For the -50 ms probe delay condition, the probe was presented, and followed by the array 50 ms after its onset. Array and probe durations were 200 and 150 ms, respectively. For positive probe delays, the array was followed by the prooe either 350, 650, 950, or 1650 ms after its onset. Coinciding with the presentation of the array a pair of dots, one 0.3 degrees of visual angle above and one 0.3 degrees below each displayed item, were presented to remind subjects which locations were filled. These dots remained in view until the subject responded. For the LP paradigm, the probe consisted of a pair of collinear vertical lines, each subtending 0.5 degrees of visual angle. The end of each line nearest the display region was positioned 0.3 degrees above (below) one of the display elements. For the MD and MN paradigms, the probe consisted of an item, positioned such that the bottom of the item was 0.3 degrees of visual angle above the top of the displayed character. Subjects' vocal response triggered a speech detector interfaced to the computer. Latency was measured from the onset of the array or probe, whichever came last. After each trial, subjects rated their confidence in their response on a four point scale:

Rating	Meaning
1	Certainly incorrect
2	Probably incorrect; guessing
3	Probably correct, but not certain
4	Certainly correct

Table 2. Four Point Confidence Rating Scale

Subjects communicated their confidence judgment by operating one of four levers positioned in front of them. Mapping between confidence judgment and fingers was as follows: confidence levels one through four were communicated using the left-middle, left-index, right-index, and right-middle fingers.

3.6 Results and Discussion

3.6.1 Data Selection

In nearly all psychological experiments in which RT is measured, subjects go through an initial learning phase during which they become acclimated to the task. During this time, RT within a condition is often highly variable, and often not representative of practical performance. Since the goal of this experiment is to gain understanding about the functioning of the cognitive system under practical conditions, in this section trends in RT and error data are examined with the goal of designating some part of the initial data collected as practice and eliminating it from consideration in analyses.

3.6.1.1 Trends in RT Data

To determine when trends in the mean and variability of RT had stabilized, means and standard deviations were calculated for each cycle by the following procedure. First, the experiment was broken down by the variables subject (1-6); cycle (1-6); paradigm (LP, MD, MN); probe delay (−50, 350, 650, 950, 1650); array size (1-5); absolute position (1-5); and serial position (1-5). Second, trials on which the subject made an incorrect response were dropped. Third, a mean and variance was calculated for the replicates within each cell, where a cell is defined by the factorial expansion of the above variables. Fourth, means and variances were averaged over levels of the relative position, then absolute position, then length, then probe delay, and finally paradigm. (Note that averaging in successive steps is required —rather than simply pooling over all factors at once— because data were not collected for all cells in the factorial expansion.) Fifth, the square root of the averaged variances was taken. Figures 3 and 4 are plots of the resulting means and standard deviations.

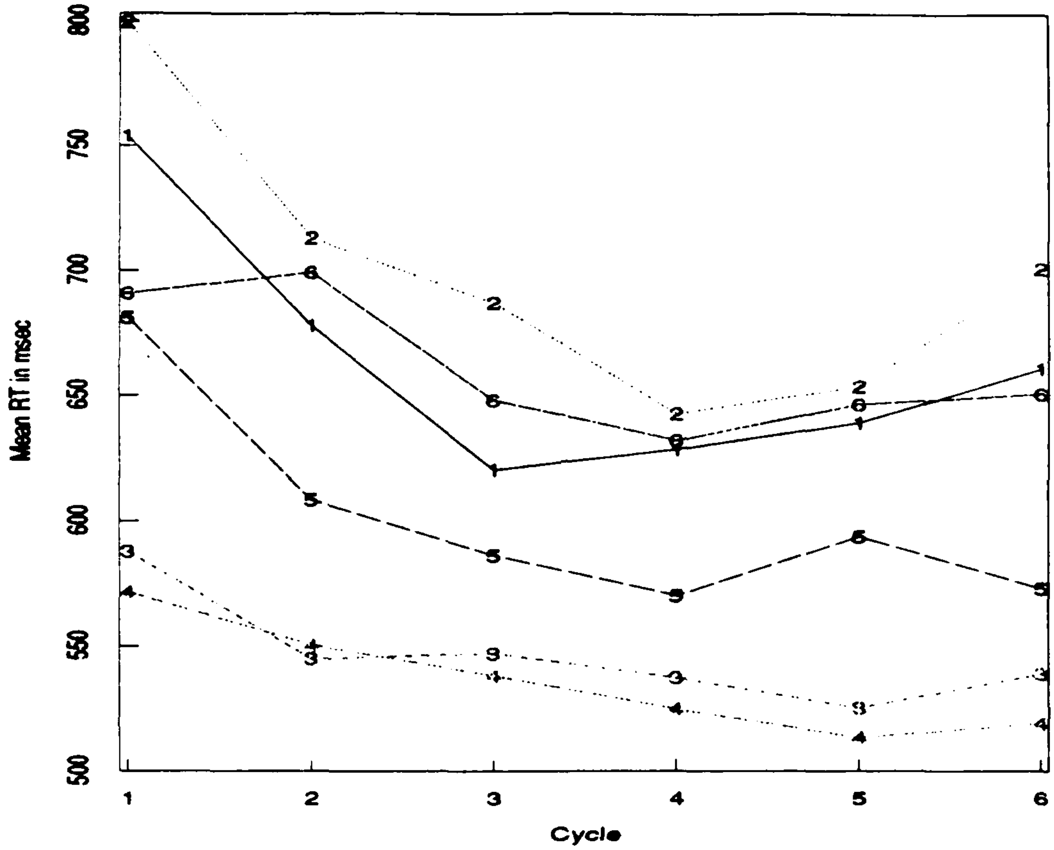

Figure 3. Mean RT by Subject and Cycle

Each curve in the figure represents one subject. The plots reveal an initial decline in mean (Figure 3) and variability (Figure 4) during the first two cycles, with greater stability being reached by the third cycle. To check this judgement, an analysis of variance (ANOVA) was performed with factors subject (1-6) and cycle (1-6). Mean latency and standard deviation did reliably differ across cycles, $F(5,25) = 16.5$, $p < .001$, and $F(5,25) = 10.5$, $p < .001$, respectively. In a second ANOVA that included only cycles three through six, neither mean latency or standard deviation differed reliably across cycles, $F(3,15) = 2.0$, $p > .16$, and $F(3,15) = 0.1$, $p > .95$, respectively.

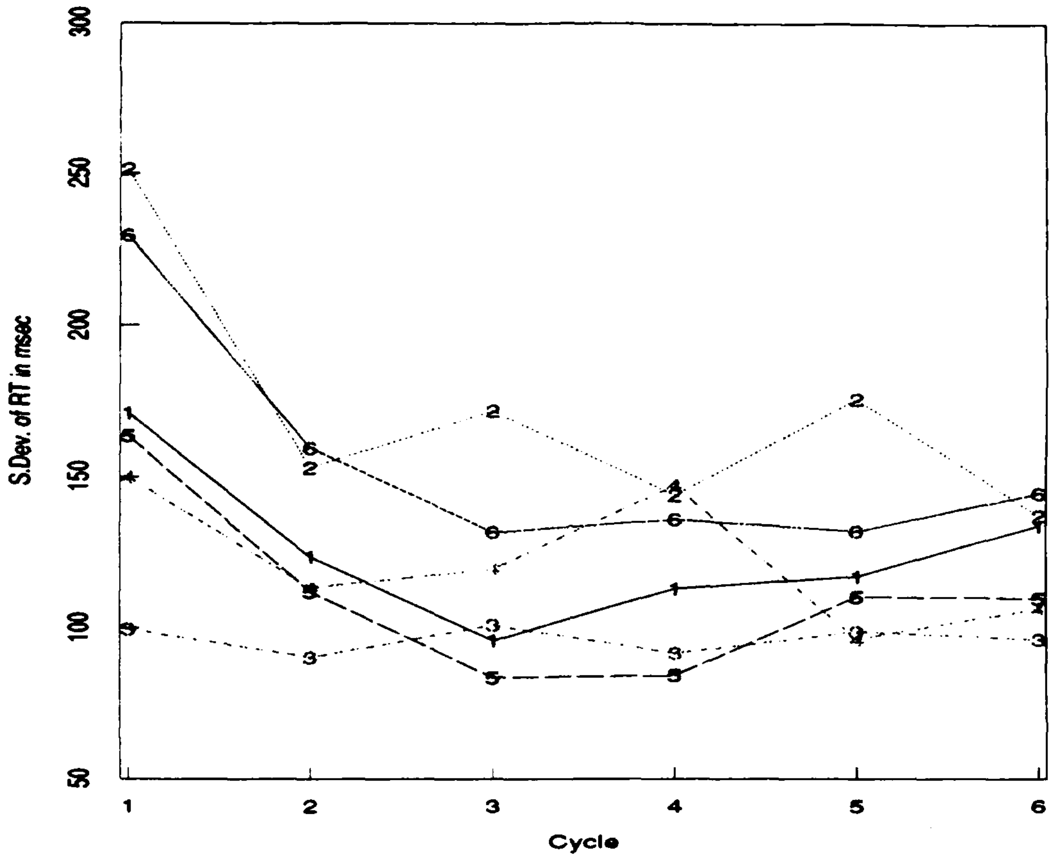

Figure 4. Standard Deviation of RT by Subject and Cycle

3.6.1.2 Trends in Error Data

Figure 5 presents error rate plotted as a function of cycle.

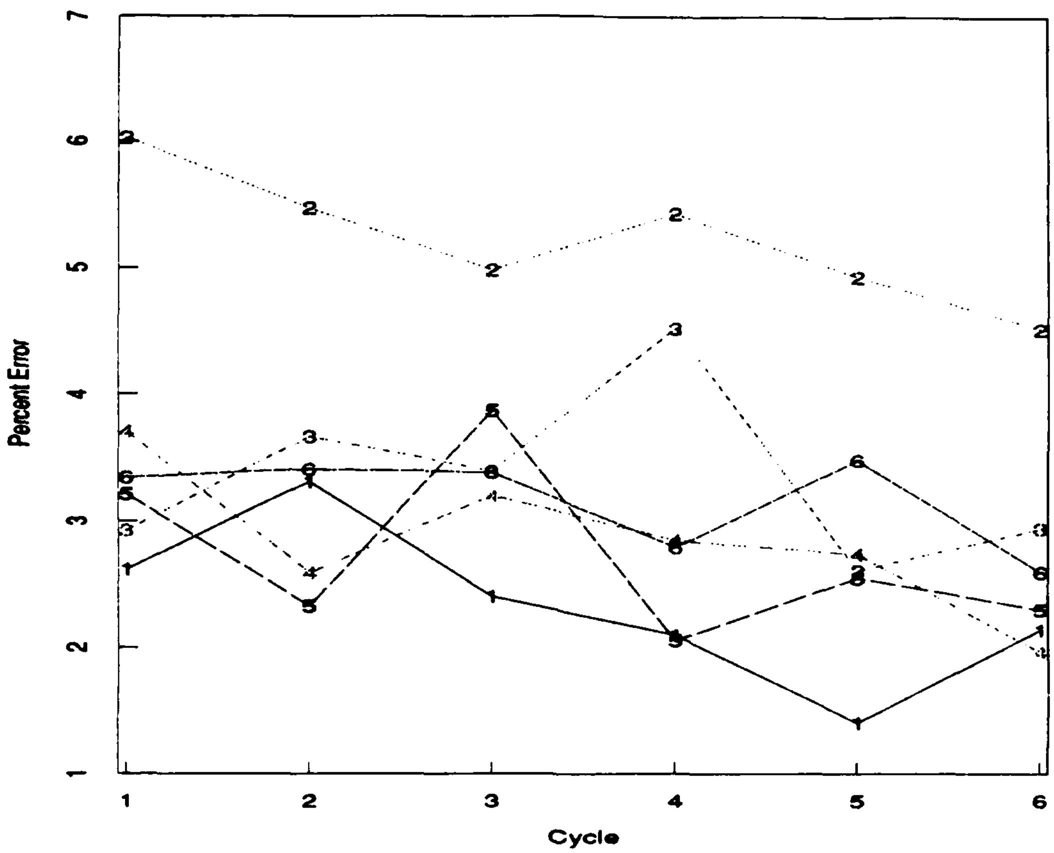

Figure 5. Percent Error by Subject and Cycle

Overall error rate for the experiment was three percent. Mean error rates (calculated by sequential averaging in a manner analogous to that used for latency) did reliably differ across cycles one through six, $F(5,25) = 5.52$, $p > .002$, but not across cycles three through six, $F(3,15) = 2.86$, $p > .07$, although errors did tend to decrease throughout the experiment.

Taken collectively, the observed trends in RT and error rates indicate it is reasonable to regard the data from cycles three through six as stable, and to restrict analyses to these data. Accordingly, data from cycles one and two were excluded from subsequent analyses.

3.6.1.3 Confidence Judgements

As noted in Section 3.5.5, subjects rated their responses on a four point confidence scale. The rationale for this was to eliminate trials on which the subject blinked, or coughed, or felt something else unusual happened that might add noise to the data. Since the goal of this experimentation is to generalize the understanding gained to the accurate functioning of the human cognitive apparatus, trials on which subjects felt they were likely to have made an error should not be included in analyses.

It is possible that selecting trials on this basis might have no effect, rendering the confidence judgment data useless. To determine if there were reliable interactions between confidence level and the experimental conditions of interest, an ANOVA was attempted with factors subject (1-6), confidence rating (1-4), delay (-50, 350, 650, 950, 1650), paradigm (LP, MD, MN), and, where appropriate, response condition (yes, no/in, no/out). However, there were so few trials on which subjects reported a confidence rating of less than three that not enough cells of the experimental design were filled to permit such an analysis. Table 3 demonstrates this fact. In the table, the number of correct response trials are given by subject and confidence level.

Confidence Rating	Subject						
	jh	cc	jp	lb	ht	mm	Σ(%)
1	0	2	3	0	3	2	.03
2	2	87	33	1	1	27	.56
3	311	263	300	60	42	371	5.0
4	4271	4069	4182	4483	4483	4101	94.4

Table 3. Number of Correct-response Trials by Subject and Confidence Rating

To determine if the elimination of low-confidence trials might have any effect, an independent-sample t-test was performed comparing the RTs from trials with a confidence rating of one or two with RTs from trials with a confidence rating of three or four. Mean RT for the former case was 1269.8; for the latter it was 597.1. The results of this test indicated a reliable difference between rating categories, $t(27095) = 45.2$, $p < .001$. Because the two categories were associated with significant differences in RT, and because of the belief that trials with a rating one or two reflect situations in which processing did not proceed normally, the relatively few trials with a confidence rating of one or two were excluded from subsequent analyses.

3.6.2 Regression Analysis

Sternberg, Knoll, & Turock (1986, Section 6) discuss some of the difficulties in designing an experiment to assess the effect of array size at different probe delays. One such difficulty is that secondary experimental factors that are known to have effects on RT may also vary from trial to trial (e.g., see Turock, 1985; Sternberg & Knoll, 1985; Sternberg, Knoll, & Turock, 1985; 1986; 1987a; 1987b). Examples of such factors are the relative and absolute position of the probed element, as well as its identity. Ideally all secondary factors should be independent of array size and probe delay, either by being held constant while these primary factors are varied, or by being varied orthogonally with the primary factors. With respect to array size there are inherent difficulties in satisfying such requirements. For example, any pairwise combination of values of relative, absolute, or array position determine the value of the third. Consequently, regardless of the size of the experiment, relative, absolute, and array position cannot simultaneously be made orthogonal with array size. Further, any experiment in which the identity of the probed item is made orthogonal with all other factors becomes impractically large. It follows, then, that a "pure" measure of the array-size effect cannot be extracted simply by employing the usual practice with unbalanced designs of assuming no interaction of this effect with levels of secondary factors, and averaging over them. Instead, in this and previous work a choice was made to design experiments so as to permit the desired "pure" measure to be extracted from a multiple linear regression analysis, in which the position effects are estimated separately. Descriptions of the regression models used to estimate effects for the three paradigms of the present experiment are now presented.

3.6.2.1 Regression Model for Location Probe Paradigm

The regression model for the LP paradigm can be stated as follows. Let α_s represent the effect of array size for size s; β_{sr} represent the relative position effect for size s and relative position r; γ_a represent the effect of absolute position for exterior elements (i.e., those at the ends of an array); λ_o represent the effect of absolute position for interior elements (i.e., those with neighboring elements on both sides); and δ_p represent the effect of the identity of the probed item. Since array size varies from one to five there are five α's (one for each size), 14 β's (one for size one, two for size two, etc.), five γ's (one for each end display location possible), three λ's (one for each inside display location possible), and ten δ's (one for each of the items, in this case the digits 0 through 9).[8] The model is

8. In the regression analyses, $s = 1$ elements were treated as having exterior absolute position status. It is possible that in the case of $s = 1$, the probed element is *neither* interior or exterior (since it has neighbors on neither side), and should be considered separately. Because of the enormous complexity in setting up the data structures and performing the regressions, however, only the exterior model was attempted.

$$T_{s,r,a,o,p} = \mu + \alpha_s + \beta_{sr} + \gamma_a + \lambda_o + \delta_p$$

To permit a unique solution, the following constraints are imposed:

$$\sum_{s=1}^{5}\alpha_s = 0$$

$$\sum_{r=1}^{s}\beta_{sr} = 0, \quad s = 1,2,3,4,5$$

$$\sum_{a=1}^{5}\gamma_a = 0$$

$$\sum_{o=1}^{3}\lambda_o = 0$$

$$\sum_{p=1}^{10}\delta_p = 0$$

To achieve these constraints, one of the α's, four of the β's, one of the γ's, one of the λ's, and one of the δ's are expressed in terms of other coefficients, i.e.,

$$\alpha_5 = -\sum_{s=1}^{4}\alpha_s$$

$$\beta_{ss} = -\sum_{r=1}^{s-1}\beta_{sr}, \quad s = 2,3,4,5$$

$$\gamma_5 = -\sum_{a=1}^{4}\gamma_a$$

$$\lambda_3 = -\sum_{o=1}^{2}\lambda_o$$

$$\delta_{10} = -\sum_{p=1}^{9}\delta_p$$

A portion of the regression design matrix for this model is presented in Appendix 1. Rows of the matrix correspond to trial types. Columns of the matrix correspond to the coefficients of the regression equation. For example, in Appendix 1 columns one through four represent the α's, five through 14 represent the β's, 15 through 18 represent the γ's, and 19 through 20 represent the λ's. The identity effect parameters (δ's) are not shown, because doing so would require ten copies of the matrix, one for each of the digit identities zero though nine. Had they been included, the complete matrix would have had an additional nine columns.

3.6.2.2 Regression Model for Matching Digits Paradigm

The regression model for the MD paradigm is identical to the one used for the LP paradigm, with the exception that the δ's represent the identity of the *target* item, not the item below it. Note that it is also possible to define another collection of parameters representing the item in the probed array location. However, attempting this further classification leads to extremely sparse data per cell; when such a regression was attempted, a number of the parameter values were found to be "underdetermined" (see Draper & Smith, 1981).

Because it is possible that the parameters for the three response conditions (yes, no/in, no/out) differ, a regression was performed for each condition in the MD paradigm, rather than including another parameter that represents condition. Another alternative would have been to test the results of the regressions for differences, then combine parameters that did not reliably differ into "supra-conditions". The former method was chosen so that ANOVAs could be performed on the parameters as if they were mean RTs. This approach allows more straightforward interpretation of effects in terms of the experimental conditions of interest.

3.6.2.3 Regression Model for Matching Nameless Shapes Paradigm

The regression model for the MN paradigm is analogous to the one used for the MD paradigm, with two exceptions, (1) only array sizes one through four enter into the model, since array-size five was not tested, and (2) there are only eight distinct δ's corresponding to the eight nameless shapes. There are thus four α's (one for each size), ten β's, four γ's, two λ's, and eight δ's

Linear constraints are again imposed on the model:

$$\sum_{s=1}^{4} \alpha_s = 0$$

$$\sum_{r=1}^{s} \beta_{sr} = 0, \quad s = 1,2,3,4$$

$$\sum_{a=1}^{4} \gamma_a = 0$$

$$\sum_{o=1}^{2} \lambda_o = 0$$

$$\sum_{p=1}^{8} \delta_p = 0$$

which are realized as follows:

$$\alpha_4 = -\sum_{s=1}^{3} \alpha_s$$

$$\beta_{ss} = -\sum_{r=1}^{s-1} \beta_{sr}, \quad s = 2,3,4$$

$$\gamma_4 = -\sum_{a=1}^{3} \gamma_a$$

$$\lambda_2 = -\lambda_1$$

$$\delta_8 = -\sum_{p=1}^{7} \delta_p$$

The regression design matrix for this model is presented in Appendix 2.

3.6.2.4 Use of Robust Regression

Sternberg, Turock, & Knoll (1986) compared ordinary least squares regression with the Huber robust method on data collected in the LP paradigm, and determined the robust method to be superior in reducing variability in parameter estimates without producing notable distortions in the data relative to several criteria of orderliness. Because of the potential for outliers in the latency data, and because of the inadequacy of conventional outlier elimination methods, the Huber method was used to analyze the data from this experiment in addition to the standard least-squares technique. Although ANOVAs did indicate reliable differences between sets of parameters obtained through the two methods, visual comparisons between plots of parameters suggested that no substantive conclusions would be changed if the least squares technique were to have been used. Because of this, and because of the belief (fostered by the Sternberg, Turock, & Knoll work) that the robust parameters provide better estimates of the "true" effects, parameters from the robust technique were used in all subsequent analyses in lieu of those from least-squares.

3.6.2.5 Summary of Array Size Parameters

To express regression coefficients as fitted mean reaction time measures, the value of the mean term (μ) from the robust regression was added to the value of each α coefficient. Such estimates are intended to provide the equivalent of mean RT from the corresponding array size under conditions where other factors are fully orthogonal with array size. Figures 6, 7, and 8 contain plots of mean fitted reaction times by probe delay and array size for the LP, MD, and MN paradigms, respectively. In the figures, curves labeled "N" indicate a naming response, "Y" indicate a trial for which "yes" was the appropriate response, "I" indicate a no/in trial, and "O" indicate a no/out trial.

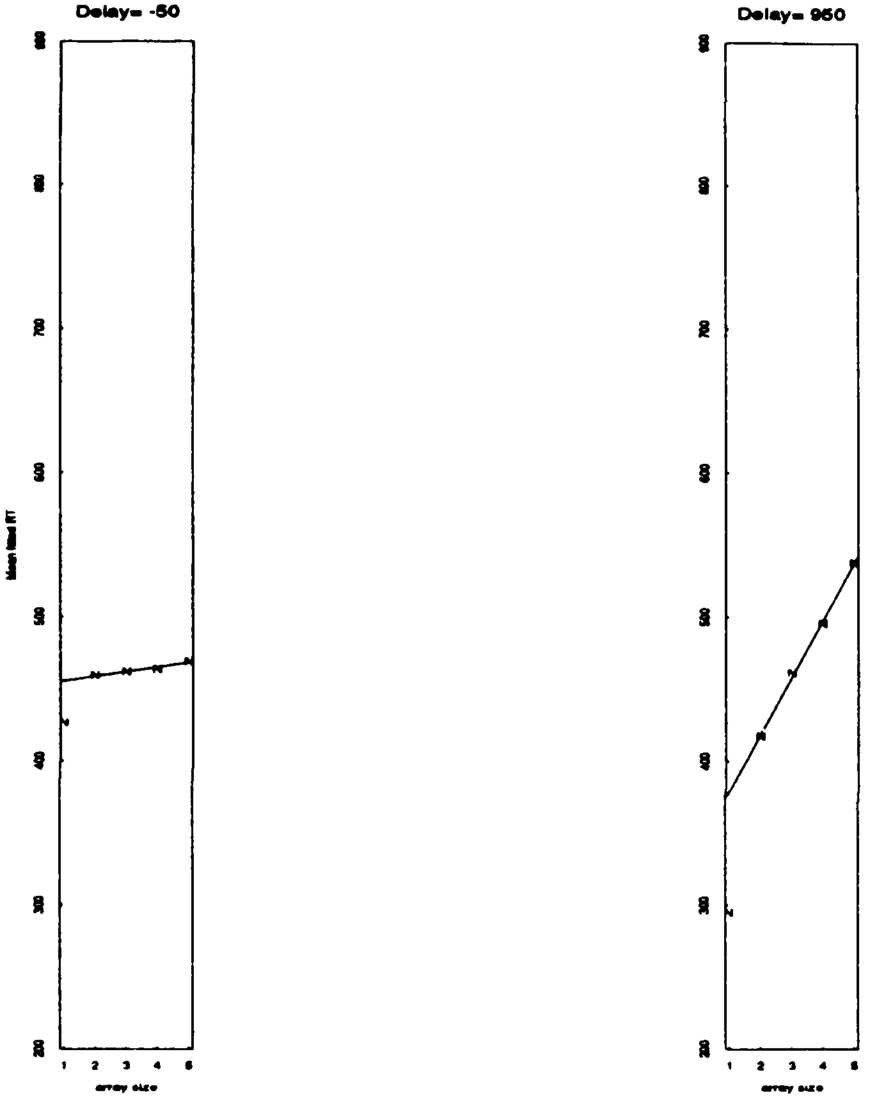

Figure 6. Mean Fitted RT for the Location Probe Paradigm

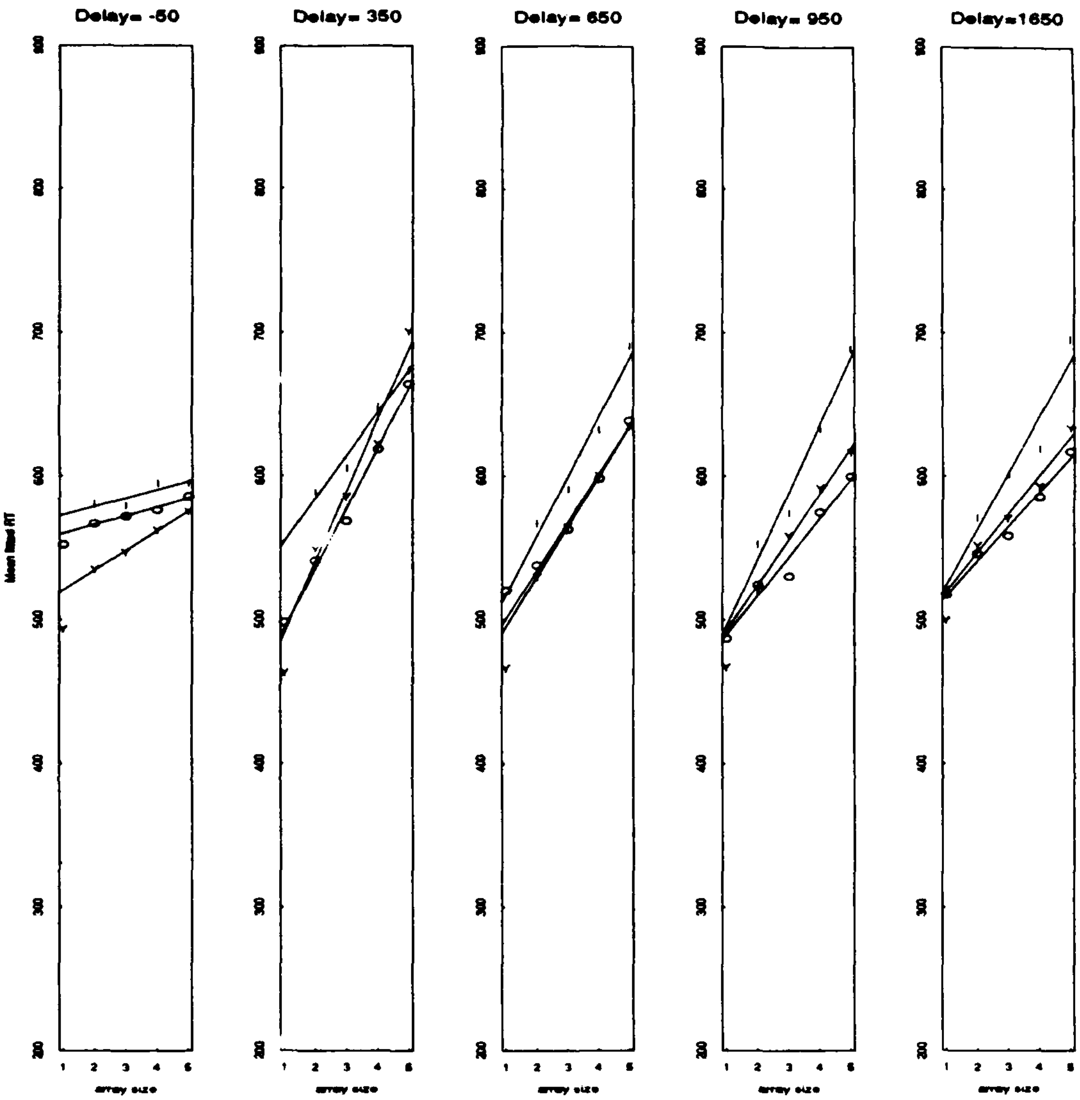

Figure 7. Mean Fitted RT for the Matching Digits Paradigm

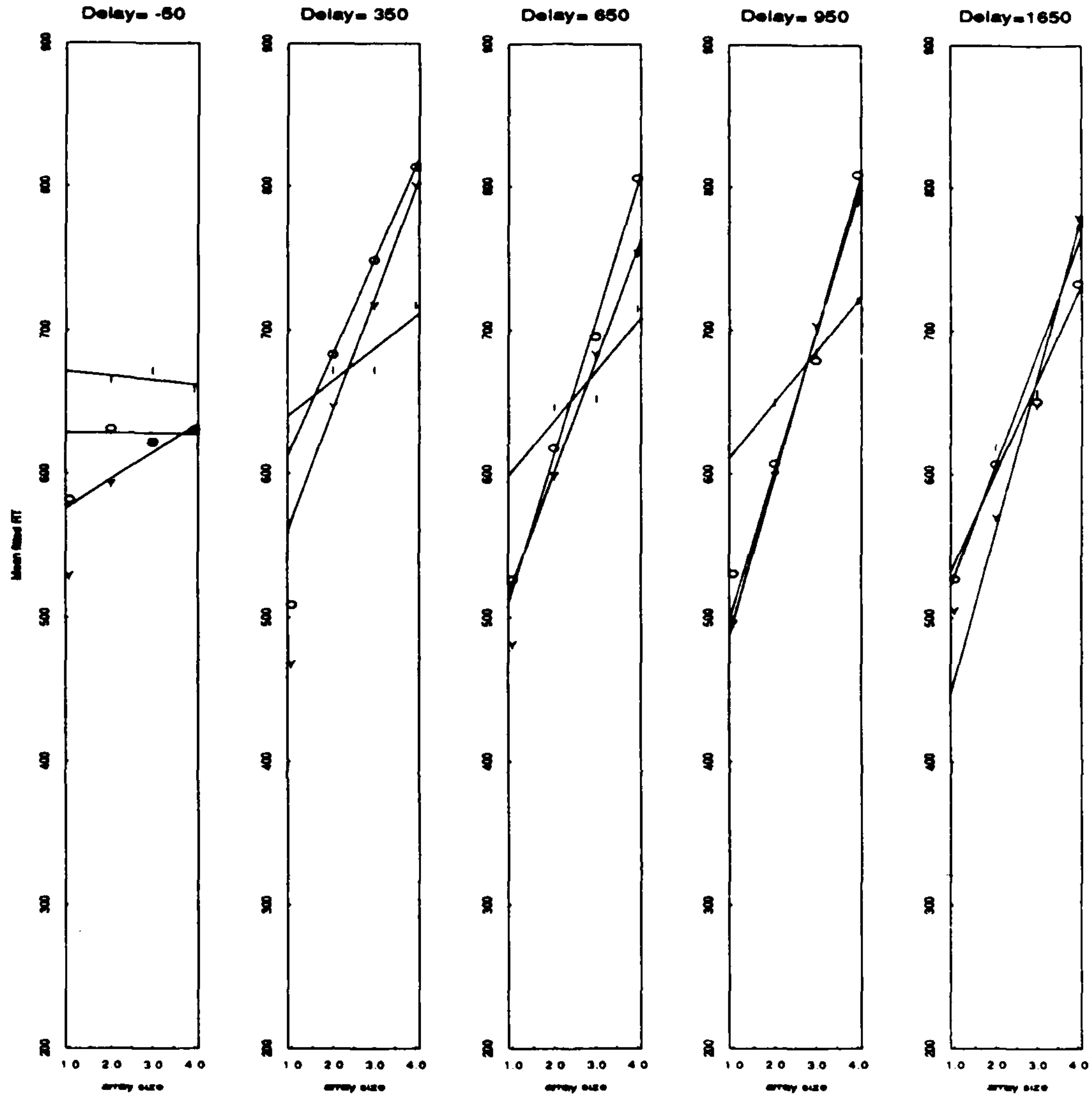

Figure 8. Mean Fitted RT for the Matching Nameless Shapes Paradigm

3.6.3 Linearity of Latency Functions

For both naming and matching paradigms, array-size one represents a special case where the subject's task differs from that on trials with array-sizes two or greater. For example, in the LP paradigm, RT in delayed probe conditions is simply the time to begin vocalization of a single displayed item, since the position of the probed item is known before the probe is presented. Similarly, for the MD and MN paradigms, in delayed probe conditions RT for array-size one trials is simply the time required to decide whether the test item is the same as a pre-specified item. Since no search need take place in any of these cases, it is not appropriate to consider parameter values from array-size one in the same context as those greater than one. Consequently, the latency functions studied in this and subsequent sections include only array-sizes two or greater.

As is evident in the figures, latency functions are approximately linear in each of the three paradigms. To determine if it was reasonable to summarize the data with the parameters of a linear function, a quantitative test of linearity was performed as follows. The α parameters for array sizes two through five (LP and MD paradigms) and two through four (MN paradigm) were extracted from the output of the robust regression described in the previous section. The mean term (μ) from the robust regression was then added to each coefficient, to convert it into a fitted reaction time measure. Least-squares regressions were then performed on these values for each valid combination of subject (1-6), paradigm (LP, MD, MN), delay (-50, 350, 650, 950, 1650), and, in the case of the MD and MN paradigms, response condition (yes, no/in, no/out). For the LP and MD paradigms, two models were examined, vis., linear ($\mu + \alpha_s = \phi + \rho s$), and quadratic ($\mu + \alpha_s = \phi + \rho s + \theta s^2$). Two goodness-of-fit measures were computed for each regression, the multiple r-square (Myers, 1979)— a measure of the percent of variance accounted for by the model— and the residual standard error (RSE), defined by the formula

$$\frac{RSS}{n - p}$$

where RSS is the sum of squared residuals, n is the number of observations in the regression (one for each α parameter), and p represents the number of fitted parameters. For the MN paradigm, both linear and quadratic models were also computed, however, since only array sizes two through four were tested, the residuals for the quadratic model were all zero.

In examining the results of these regressions, it is evident that the quadratic model did produce lower values of RSE than the linear model in several cases. The average gain in percent of variance accounted for was minimal, however (4, 4.7, and 4.7 percent, for the LP, MD, and MN conditions, respectively). To facilitate straightforward comparisons between conditions it is desirable to choose a single model. The linear model was chosen on the grounds of parsimony. Since this choice could bias conclusions if the value of θ changed reliably with the experimental conditions of interest, a separate ANOVA was performed for each paradigm on the value of θ. Factors in the analyses included subject, delay, and (in the case of the MD and MN paradigms) response condition. No reliable ($p < .05$) effect of delay, response condition, or the interaction of the two was evident in any of these analyses. It was thus concluded that use of the linear model is reasonable way to summarize the data.

Table 4 presents mean slopes and between-subject standard errors of slopes from the linear fits for each of the conditions of the experiment. In the table, LP represents data from the Location Probe paradigm, MD represents data from the Matching Digits paradigm, and MN represents data from the Matching Nameless paradigm. Identifiers in parenthesis indicate the response condition within each paradigm: (y) indicates a parameter for "yes" response trial, (n/i) indicates a parameter for a no/in trial, and (n/o) indicates a parameter for a no/out trial.

Paradigm/ Condition		Probe Delay -50	350	650	950	1650
LP	Mean	3.1			39.6	
	SE	1.5			3.1	
MD(y)	Mean	13.7	49.3	34.9	31.9	26.7
	SE	2.0	7.9	4.5	4.9	5.0
MD(n/i)	Mean	5.7	29.8	41.2	46.8	39.0
	SE	3.0	9.0	6.5	8.6	6.3
MD(n/o)	Mean	6.1	41.9	33.6	27.1	24.0
	SE	2.7	5.9	5.2	2.7	5.8
MN(y)	Mean	28.7	67.2	79.9	99.8	100.3
	SE	10.6	22.7	12.6	19.4	17.1
MN(n/i)	Mean	3.1	25.5	44.4	45.7	81.0
	SE	7.8	10.1	16.5	17.4	9.9
MN(n/o)	Mean	-4.3	84.1	115.9	96.7	66.7
	SE	6.8	29.9	28.0	24.5	10.1

Table 4. Mean Slopes and Standard Errors of Slopes by Probe Delay and Condition

3.6.4 Processing Models

To facilitate analysis of the present experiment, models of the cognitive processing mechanisms underlying performance are now considered. A series of models are presented and predictions made by these models are compared to observed patterns in the data. It is demonstrated that while some of the models fit the data better than others, none can adequately account for all the patterns observed.

One reason for attempting to formulate quantitative descriptions of the models is to guide the choice of a dependent measure that includes that part of RT which is due to processes independent of array size. It is demonstrated that the appropriate choice for such a measure is an intercept (e.g., zero-intercept, one-intercept, etc.) of the linear function relating RT to array size. However, since none of the models fit the data particularly well, the exact intercept to study can not be determined. An upper and lower bound for the intercept is thus derived; all intercepts within the limits of this bound are then studied in subsequent analyses.

3.6.4.1 Notation for Models

Some definitions are required for the discussion of models. Let

s = the number of items in the array (array size)
R_s = the mean reaction time for array size s
η_d = the mean duration of all non–search processes in the location probe task
η_p = the mean duration of all non–search processes in positive responses
η_n = the mean duration of all non–search processes in negative responses
ω = 1 – Pr(direct access)
Ψ = the mean duration of a matching location comparison
ψ = the mean duration of a mismatching location comparison
Π = the time for a matching identity comparison
π = the time for a mismatching identity comparison

$$\xi = \begin{cases} 1 & \text{if a yes trial} \\ 0 & \text{otherwise} \end{cases}$$

3.6.4.2 Data Structure for Models

To facilitate concise expression of models, a data structure for items in memory is now described. Let e represent a single element in a displayed array. There are thus s elements in an array of size s, which will be denoted $e[1]$, $e[2]$, ..., $e[s]$. Each element contains two components of information, its *location*, denoted $e[r].loc$ for the element in the r^{th} relative position, and its *identity*, denoted $e[r].id$ for the r^{th} element. (The identity component may be regarded as equivalent to "name" in the case of the LP paradigm, and "shape" or "feature collection" in the MD and MN paradigms.) For the LP paradigm, the probe has one component, denoted $p.loc$, for location; for the MD and MN paradigms the probe has two components, $p.loc$ for location and $p.id$ for identity.

3.6.4.3 Initial Assumptions

It is assumed that: (1) The process that depends on array size is one of serial search without replacement.[9] (2) The number of mismatching comparisons is the only process difference between array sizes. (3) ω may take on a continuum of values from zero to one; that is, the presence of direct access is probabilistic. To simplify model exposition, however, ω will be restricted to the values zero or one. (4) The memory representation has the property that when $e[r].loc$ has been accessed, $e[r].id$ is immediately accessible, and vice-versa. (5) When direct access is present the subject is able to access the location of the probed item directly by using $p.loc$ as an index into the $e[r]$'s, i.e., the subject retrieves $e[p.loc].id$.

3.6.4.4 Model for Location Probe Paradigm

The model for the LP paradigm is essentially that of Sternberg, et al. (1975): when direct access is present, the subject accesses the location of the probed element (p.loc) directly and without sequential search. The identity $e[p.loc].id$ is then extracted and the corresponding name verbalized. When direct access is absent, the subject searches through the $e[r]$ for an $e[r].loc$ equal to $p.loc$. Upon finding a match, $e[r].id$ is extracted, and the appropriate name verbalized.

In the presence of direct access (i.e., $\omega = 0$) the equation describing mean RT is $R_s = \eta_d$ where d indicates that the response is the spoken name of a digit. In the absence of direct access, search may proceed in one of two ways. If it is self-terminating then the number of elements in the set of mismatches is equiprobable among $\{0, 1, 2, ..., s-1\}$. The mean number of mismatches is then $\frac{(s-1)\,s}{2}/s$, or $\frac{s-1}{2}$. The equation describing mean RT is thus $R_s = \eta_d + \omega\,\Psi + \omega\,\psi\,\frac{s-1}{2}$. If search is exhaustive, the equation becomes $R_s = \eta_d + \omega\,\Psi + \omega\,\psi\,(s-1)$, since the number of required mismatching location comparisons is always $s - 1$.

In either case, the one-intercept (i.e., the value of the appropriate R_s function above when $s = 1$) is the correct choice for a measure of the components of RT that are independent of array size.

3.6.4.5 Models for Matching Paradigms

When direct access obtains, the subject accesses the location of the probed element directly and without sequential search. The identity is then extracted and compared to $p.id$. If the two match, the subject emits a "yes" response; if they do not, a "no" response is given.

There are at least four generalizations of the LP model that lead to plausible models of processing in the matching paradigms when direct access is absent.

3.6.4.5.1 Model 1: Search though Locations

In the first model, a search through locations analogous to the one hypothesized for the LP paradigm takes place. When $p.loc$ matches $e[r].loc$, a comparison between $p.id$ and $e[r].id$ is made. If a match is detected, the subject emits a "yes" response; if not, a "no" response. Under this model, if search is self-terminating, the equation describing mean RT is $R_s = \eta_m + \omega\,\psi\,\frac{s-1}{2} + \omega\,\Psi + \xi\,\Pi + (1-\xi)\,\pi$. (To

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9. This assumption may be overly simplistic. Other equally plausible models might include both serial and parallel search components. The approximate linearity of latency functions described in Section 3.6.3, however, suggests that the assumption of a serial model is reasonable.

facilitate more concise presentation of the equations describing the matching models, in this equation, and those that follow, the m subscripting the η should be read as y for positive response trials, and n for negative response trials. That is, each printed equation represents *two* actual equations, one for positive responses, and one for negative responses.) If search is exhaustive, the equation becomes $R_s = \eta_m + \omega\,\psi\,(s-1) + \omega\,\Psi + \xi\,\Pi + (1-\xi)\,\pi$. In both cases, the one-intercept is the appropriate choice for a measure of the components of RT that are independent of array size.

3.6.4.5.2 Model 2: Search through Identities

In the second model, a search though identities takes place. When *p.id* matches *e[r].id* a comparison between *p.loc* and *e[r].loc* is made. If a match is detected, the subject emits a "yes" response; if not, a "no" response. For this model, if the search is self-terminating then for yes and no/in trials mean RT is described by $R_s = \eta_m + \omega\,[\pi\frac{s-1}{2} + \Pi + \xi\,\Psi + (1-\xi)\,\psi]$. If the search is exhaustive, the equation for the yes and no/in trials becomes $R_s = \eta_m + \omega\,[\pi(s-1) + \Pi + \xi\,\Psi + (1-\xi)\,\psi]$. For yes and no/in conditions, search can be either self-terminating or exhaustive; for no/out trials search must, by definition, be exhaustive, since the none of the items in the array will have the same identity as the probe. The equation describing mean RT in this case is $R_s = \eta_n + \omega\,\pi\,s$. Consequently, for yes and no/in trials for both self-terminating and exhaustive search models the one-intercept is the appropriate for a measure of the components of RT that are independent of array size. For no/out trials, the zero-intercept is the appropriate choice for such a measure.

3.6.4.5.3 Model 3: Sequential Search through Identity and Location Information

In the third model, search proceeds by making two comparisons (*p.loc* with *e[r].loc* and *p.id* with *e[r].id*) for each item accessed.[10] If the search is self-terminating, mean RT is described by $RT_s = \eta_y + \omega\,[(\psi+\pi)\,\frac{s-1}{2} + \Psi + \Pi]$, for yes trials; $RT_s = \eta_n + \omega\,[(\psi+\pi)\,\frac{s-1}{2} + \Psi + \pi]$, for no/in trials (if a location match accomplishes first); $RT_s = \eta_n + \omega\,[(\psi+\pi)\,\frac{s-1}{2} + \psi + \Pi]$, for no/in trials (if an identity match accomplishes first); and $RT_s = \eta_n + \omega\,[(\psi+\pi)\,\frac{s-1}{2} + \Psi + \pi]$, for no/out trials. If the search is exhaustive in any of these cases the $\frac{s-1}{2}$ component in the equation is replaced by $(s-1)$. Consequently, the one-intercept is the appropriate choice for a measure of the components of RT that are independent of array size whether the search is self-terminating or exhaustive.

3.6.4.5.4 Model 4: Simultaneous Search through Identity and Location Information

In the fourth model, location and identity information is assumed to be conjoined; comparisons are made between the *conjunction* of location and identity information from the probe, and analogous conjunctions for each of the elements in the array. According to this model only one comparison per array element is necessary. Let Σ represent the time for a binary match (i.e., a match between the conjoined location and identity information of the probe and the same information from an element in the array) and σ represent the time for a binary mismatch. If the search is self-terminating, mean RT is described by $RT_s = \eta_m + \omega\,[\sigma\,\frac{s-1}{2} + \xi\,\Sigma + (1-\xi)\,\sigma]$. If the search is exhaustive the model becomes $RT_s = \eta_m + \omega\,[\sigma\,(s-1) + \xi\,\Sigma + (1-\xi)\,\sigma]$. Consequently, the one-intercept is again the appropriate choice for a measure of the components of RT that are independent of array size whether the search is self-terminating or exhaustive.

3.6.4.6 Rejection of Models 1 through 4

Each of the models for the LSM paradigm can be rejected on the basis of patterns observed in the data. For example, since the search prescribed in Model 1 accesses only *p.loc* and *e[r].loc* until the two

10. For the sake of simplicity, this model assumes that the two comparisons are accomplished sequentially, and without any overhead time for switching between the two kinds of comparisons.

match, no significant effects of out of location probes should be evident. The presence of significant differences in intercepts (examined in subsequent sections) between no/in and no/out trials in both MD and MN paradigms allow this model to be rejected. Further, *none* of the models predict differences in slope between yes, no/in, and no/out conditions. The existence of significant differences between these conditions (discussed in Section 3.6.6) indicates that either (1) there must be more than one array-size dependent process, most likely a second serial search that occurs with different probability under the different conditions; or (2) it must be known in advance of the serial search process that the probe's identity appears somewhere in the array. Accordingly, additional models were constructed that incorporated these two possibilities. These modeling efforts became enormously complex, and did not produce a model capable of explaining observed patterns in the data in all conditions. It appears that to account for all the data would require generating separate models for most of the cells in a paradigm (MD, MN) by condition (yes, no/in, no/out) by delay (-50, 350, 950, 1650) table. Clearly the generality (and usefulness) of such a collection of models is questionable.

3.6.5 Choice of an Intercept

The choice of intercept (i.e., zero-intercept, one-intercept, etc.) to study is not arbitrary: an intercept is desired that measures the part of response latency that does not include time taken up by processes dependent on array size. To choose an intercept thus requires that assumptions be made about the underlying processes involved. Models of these processes were presented in the previous section. Unfortunately, since all the models failed in some way, selection of a single intercept to study is not possible. Instead, only a range of intercepts may be specified. The intercept desired is the point where the RT vs array-size function crosses the origin. To determine this point, the value of s where the slope term drops outs of the equation must be determined. If we make the assumptions outlined in Section 3.6.4, it is possible to bound the intercept. The lower bound on the intercept must be zero, since the greatest number of mismatches possible will be equal to the number of elements in the array, s, and the slope term(s) in the function will cancel out when $s = 0$. The upper bound on the intercept can be computed by determining the lower bound on mismatches. In a serial search process, on average at least half the comparisons must result in a mismatch. Thus, as derived in Section 3.6.4.4 above, the mean number of mismatches is $\frac{s-1}{2}$, and the one-intercept is the appropriate choice. Since the modeling efforts did not lead of a clear choice of intercept, in subsequent sections both zero- and one-intercepts are analyzed. Where interpretations or conclusions are affected by choosing one intercept term over another, it is so noted. Table 5 presents the mean values of intercepts averaged over subjects and the associated between-subjects standard errors.

		Probe Delay (ms)				
		-50	350	650	950	1650
Condition						
LP	Mean	455.6			379.1	
(one-int)	SE	16.3			12.0	
MD(y)	Mean	507.1	441.6	459.9	460.5	493.8
(zero-int)	SE	22.4	43.2	30.6	26.1	30.6
MD(y)	Mean	520.8	490.9	494.9	492.4	520.5
(one-int)	SE	21.6	38.5	26.8	25.0	27.9
MD(n/i)	Mean	567.5	524.7	475.9	448.3	485.5
(zero-int)	SE	25.6	49.1	16.7	12.1	24.2
MD(n/i)	Mean	573.2	554.5	517.1	495.1	524.5
(one-int)	SE	23.7	41.6	16.1	9.5	21.6
MD(n/o)	Mean	554.1	451.6	466.8	462.4	493.5
(zero-int)	SE	16.2	34.2	33.8	23.5	30.9
MD(n/o)	Mean	560.2	493.5	500.4	489.6	517.4
(one-int)	SE	17.0	29.6	29.5	21.8	27.9
MN(y)	Mean	560.1	538.2	458.1	415.3	384.1
(zero-int)	SE	21.7	59.5	45.5	35.1	47.4
MN(y)	Mean	588.8	605.4	538.0	515.1	484.4
(one-int)	SE	22.4	47.9	43.9	31.0	37.2
MN(n/i)	Mean	674.5	626.9	562.3	573.3	468.6
(zero-int)	SE	29.2	28.0	40.4	35.2	31.7
MN(n/i)	Mean	677.6	652.4	606.7	619.0	549.6
(one-int)	SE	25.4	20.6	27.8	22.6	30.0
MN(n/o)	Mean	663.2	537.8	417.7	432.4	487.2
(zero-int)	SE	43.2	54.4	39.0	56.6	31.1
MN(n/o)	Mean	659.0	621.8	533.6	529.1	553.8
(one-int)	SE	37.8	33.4	31.3	39.2	29.3

Table 5. Intercepts and Standard Errors of Intercepts by Probe Delay and Condition

Figures 9, 10, and 11 show intercepts by delay. Table 6 is a key for the three figures.

Condition	Intercept	Label
LP	One	1
MD(y)	Zero	2
	One	3
MD(n/i)	Zero	4
	One	5
MD(n/o)	Zero	6
	One	7
MN(y)	Zero	8
	One	9
MN(n/i)	Zero	0
	One	a
MN(n/o)	Zero	b
	One	c

Table 6. Key for Intercept Plots

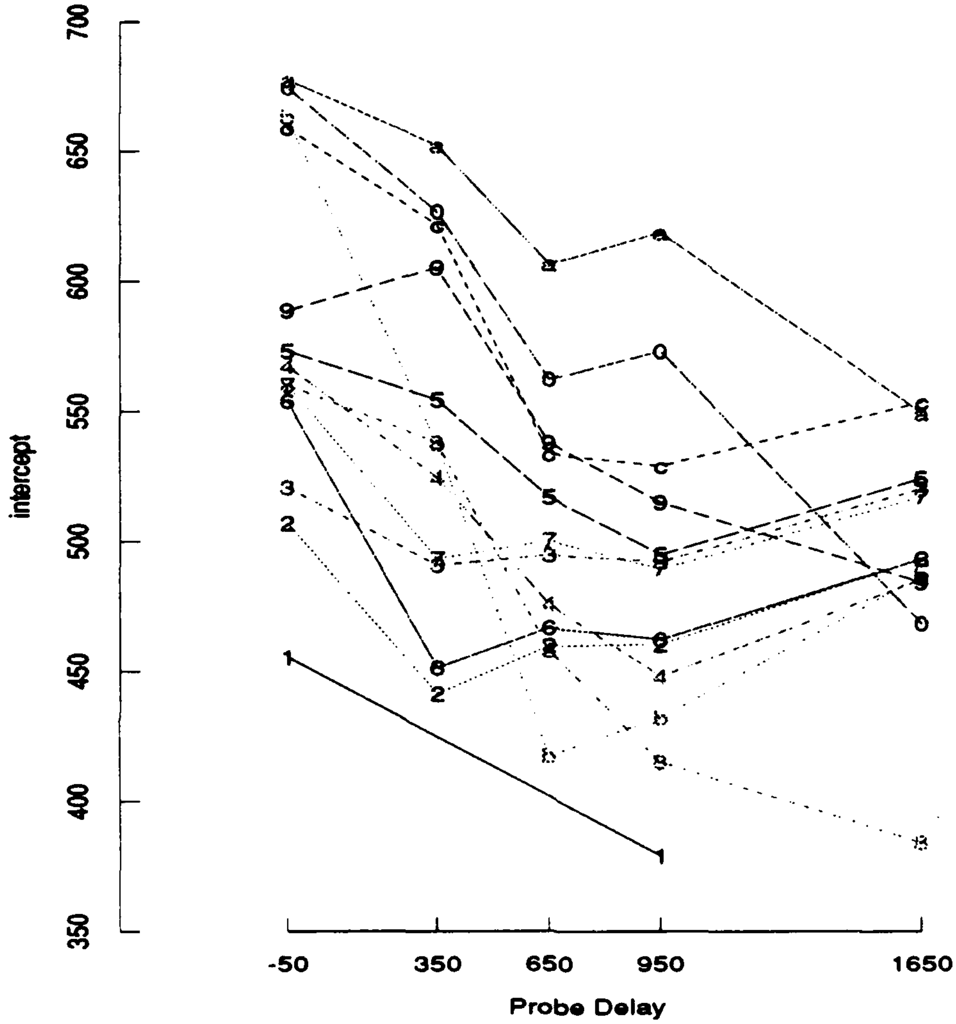

Figure 9. Mean Intercepts by Delay

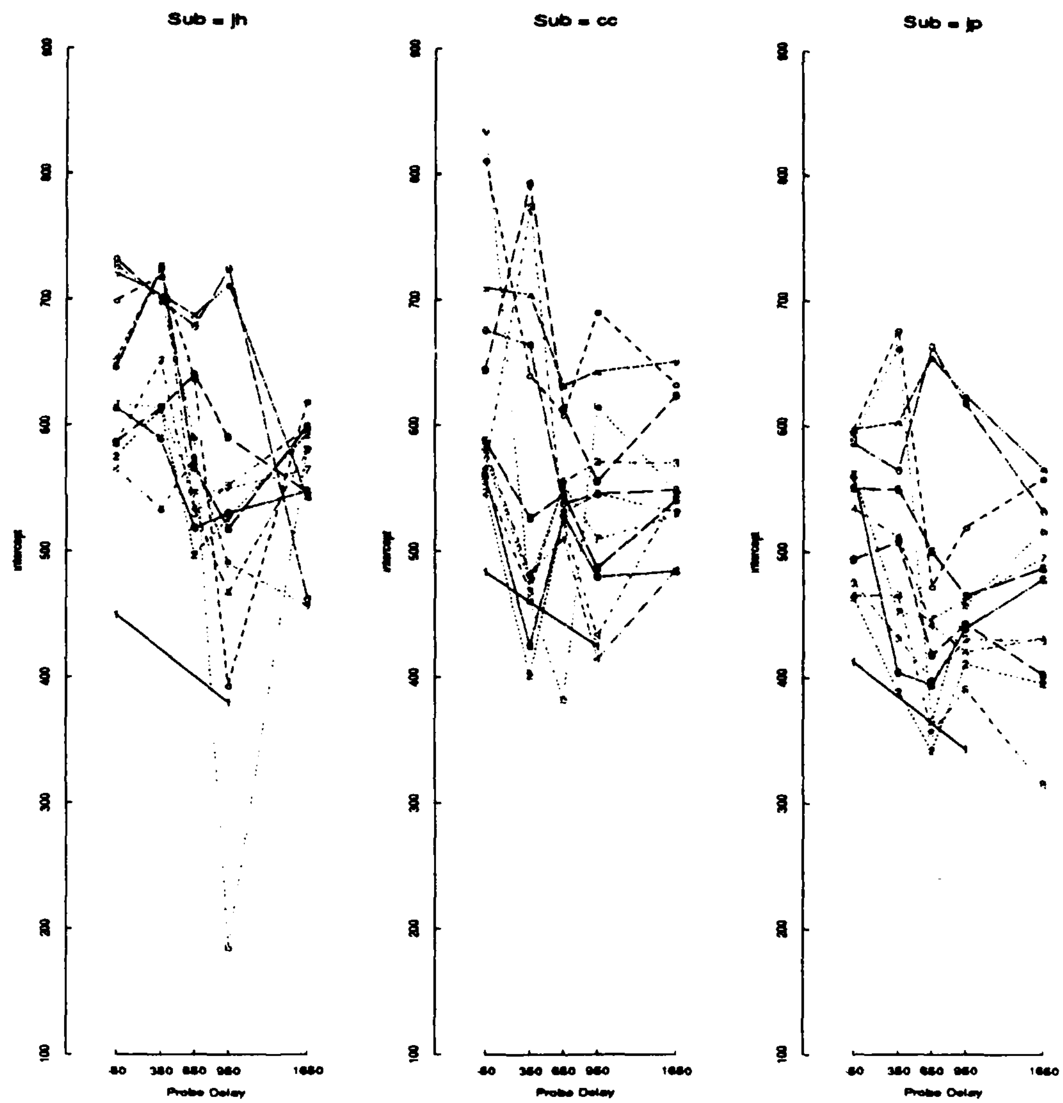

Figure 10. Intercepts by Delay for Subjects 1-3

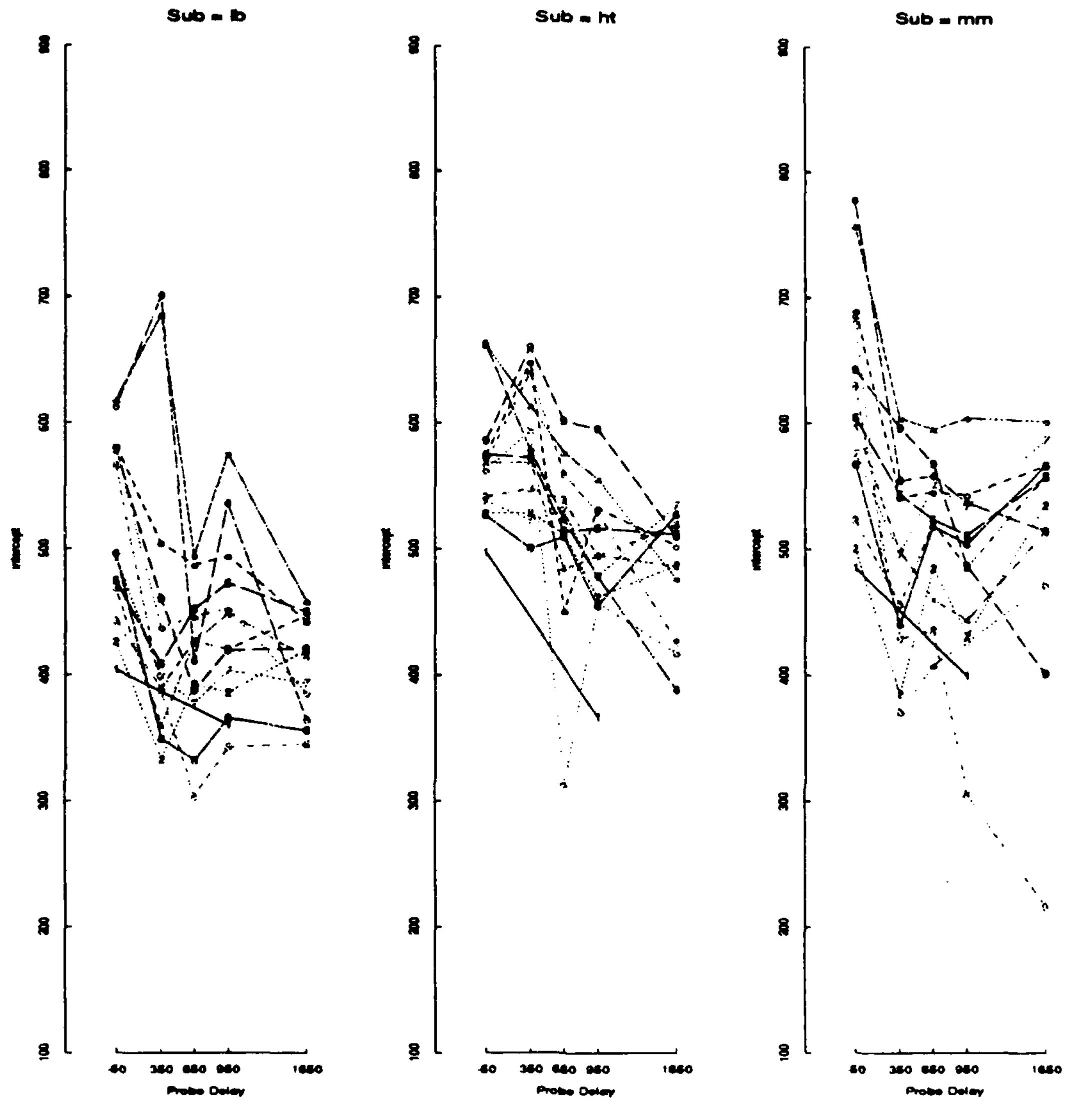

Figure 11. Intercepts by Delay for Subjects 4-6

3.6.6 Evidence for a Transformation

The slope of the latency function provides an index of the state of the internal memory representation. If slopes are near zero, the representation of displayed material is directly accessible by spatial position; serial search among array elements is not required. If slopes are markedly greater than zero, this suggests a representation that requires serial search to find an item in memory. Significant changes in slope as a function of probe delay thus indicate that a transformation from one memory state to another has taken place. To determine whether reliable differences between slopes associated with different probe delays exist, a one-way ANOVA was performed for each of the seven combinations of paradigm and response condition, with delay as the independent variable.[11] In this analysis and all subsequent ones, the "subjects" factor was regarded as a random effect; others were regarded as fixed

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11. This analysis could also performed as a two-way ANOVA for the matching paradigms, with response condition (i.e., yes, no/in, no/out) as the second factor. However, for the present we wish only to determine if a main effect of delay is present. The interaction of response condition and delay is examined in subsequent sections.

effects. Table 7 summarizes the results of these analyses.

Paradigm/ Condition	Mean Square	df	F	p
LP	3988.9	1,5	176.0	.000
MD(y)	1003.8	4,20	6.9	.001
MD(n/i)	1571.6	4,20	9.0	.000
MD(n/o)	1067.4	4,20	10.7	.000
MN(y)	5226.3	4,20	5.8	.003
MN(n/i)	4965.5	4,20	7.8	.001
MN(n/o)	12789.0	4,20	5.0	.006

Table 7. Results of ANOVA on Slopes

As is evident in the table, all analyses revealed a significant main effect of delay, $p < .05$. It is thus reasonable to conclude that a transformation occurred in *all* of the paradigms and conditions.[12]

3.6.7 Detailed Analysis of the Transformation

The analyses of the previous section indicate that a reliable change in slope occurs in each condition of the experiment. In this section, details of this slope change are examined. Figure 12 presents slopes (averaged over subjects) as a function of delay for each of the experimental conditions.

12. It is well to make explicit the underlying rule of inference employed here, namely that within either matching paradigm if *any* of the three response conditions were to reveal a reliable difference in slope, then one should conclude that some form of transformation occurs in that paradigm.

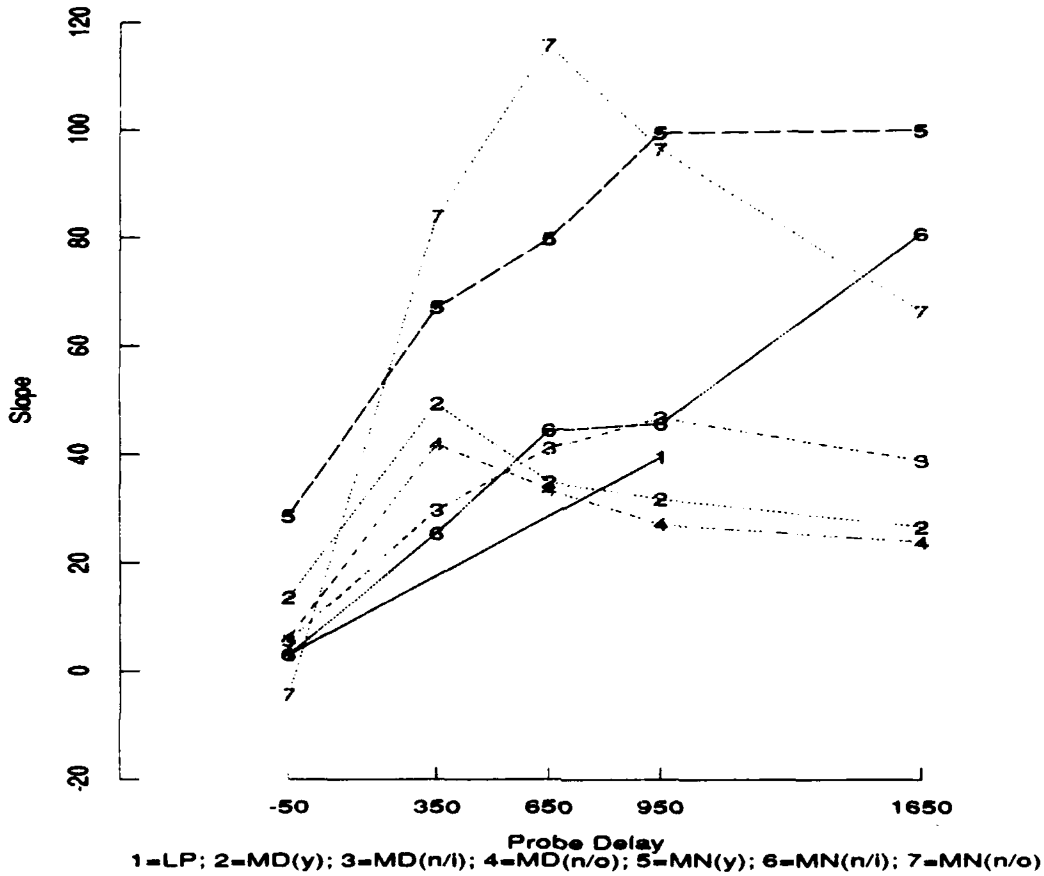


Figure 12. Average Slope as a Function of Probe Delay

To determine which of the individual slope differences were reliable, Duncan's Multiple Range Tests were performed in conjunction with each of the ANOVAs of the previous section, with the overall probability of error set at .05. The results of these tests are summarized in Table 8. Rows of the table represent combinations of paradigm and response condition; columns represent delays. Slopes that are not significantly different from each other are grouped by the same letter in a row.

Condition	Probe Delay -50	350	650	950	1650
LP	a			b	
MD(y)	a				a
		b	b		
			c	c	c
MD(n/i)	a	b	b	b	b
MD(n/o)	a				
		b	b		
			c	c	c
MN(y)	a	a	a		
		b	b	b	b
MN(n/i)	a	a			
		b	b	b	
			c	c	c
MN(n/o)	a	b	b	b	b

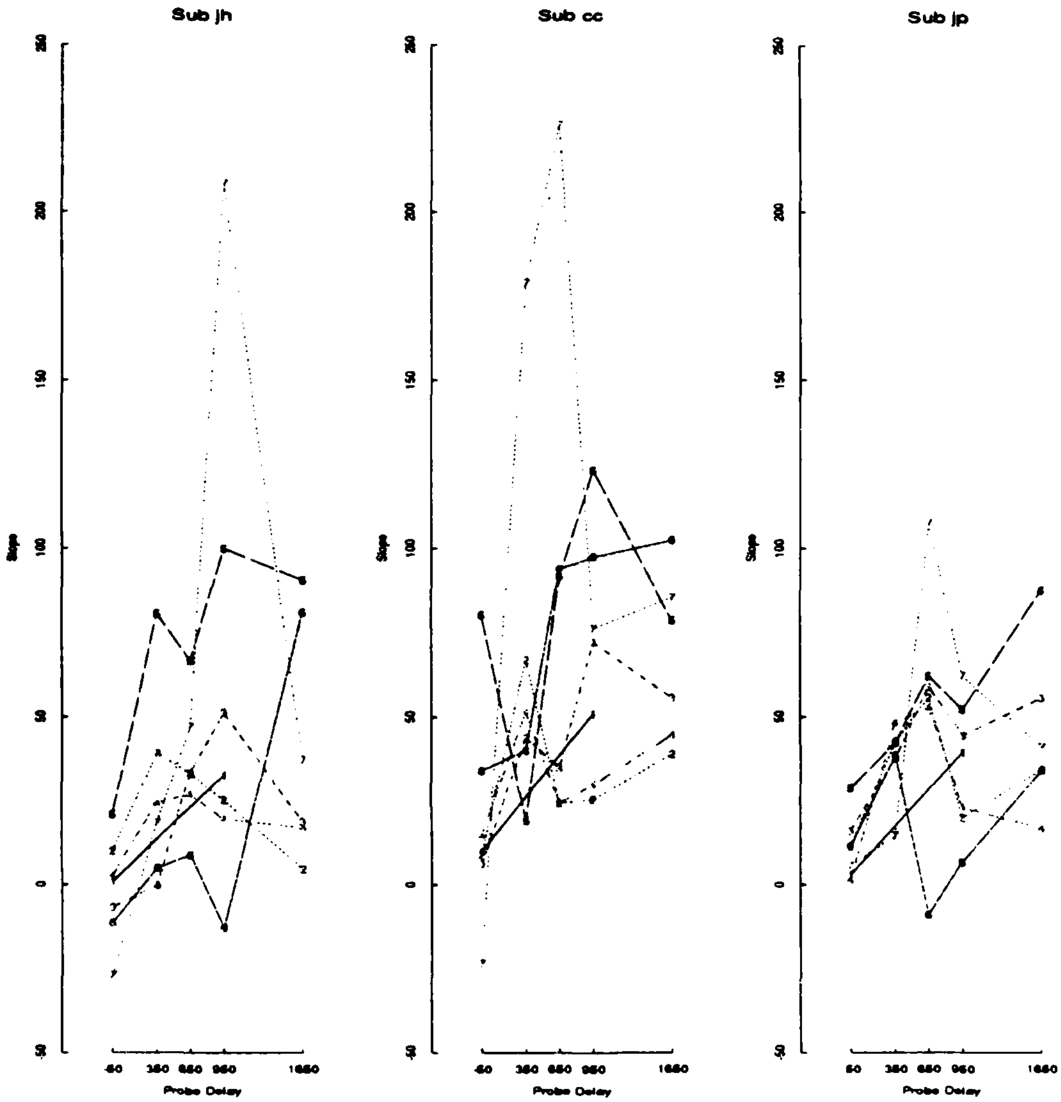
Table 8. Results from Duncan's Multiple Range Tests on Slopes

In the Sternberg et al. experiments slope changes followed a specific pattern: slopes were near zero for negative and small positive delays, and increased monotonically with increases in delay up to delays of 1650 ms.[13] Consistent with this finding, in the present experiment mean slope for the LP paradigm is near zero for the -50 delay, and large and positive for the 950 delay. For the MD(y) condition, mean slope at the -50 delay is reliably less than the slopes associated with later delays, with the exception of the 1650 delay. For MD(n/i), slopes cluster into two groups, the slope associated with the -50 delay, and slopes associated with later delays. For the MD(n/o) condition three clusters of slopes by delay are evident, {-50}, {350, 650}, and {650, 950, 1650}. For the MN(y) condition the slope at the -50 delay is reliably lower than slopes for the 950 and 1650 delays. Three clusters of slopes are apparent for the MN(n/i) condition: {-50, 350}, {350, 650, 950}, and {650, 950, 1650}. In the MN(n/o) condition, the slope at the -50 delay is reliably different from slopes for all other delays.

In all except the yes response conditions, values of slope are near zero for the -50 probe delay and reliably increase at the 350 delay. For only one condition, MN(n/i), does the slope continue to increase beyond the 350 delay. For the MD(n/i), MN(y), and MN(n/o) conditions no further changes in slope are reliable; for the MD(y) and MD(n/o) conditions slopes reliably *decrease*. This pattern is unexpected, given earlier pilot work (Turock, 1985) that suggested most of the changes in slope would occur between probe delays of 350 and 1650 ms. It appears that this conclusion may have been misleading; another experiment in which at least one delay between -50 and 350 is studied would be helpful.

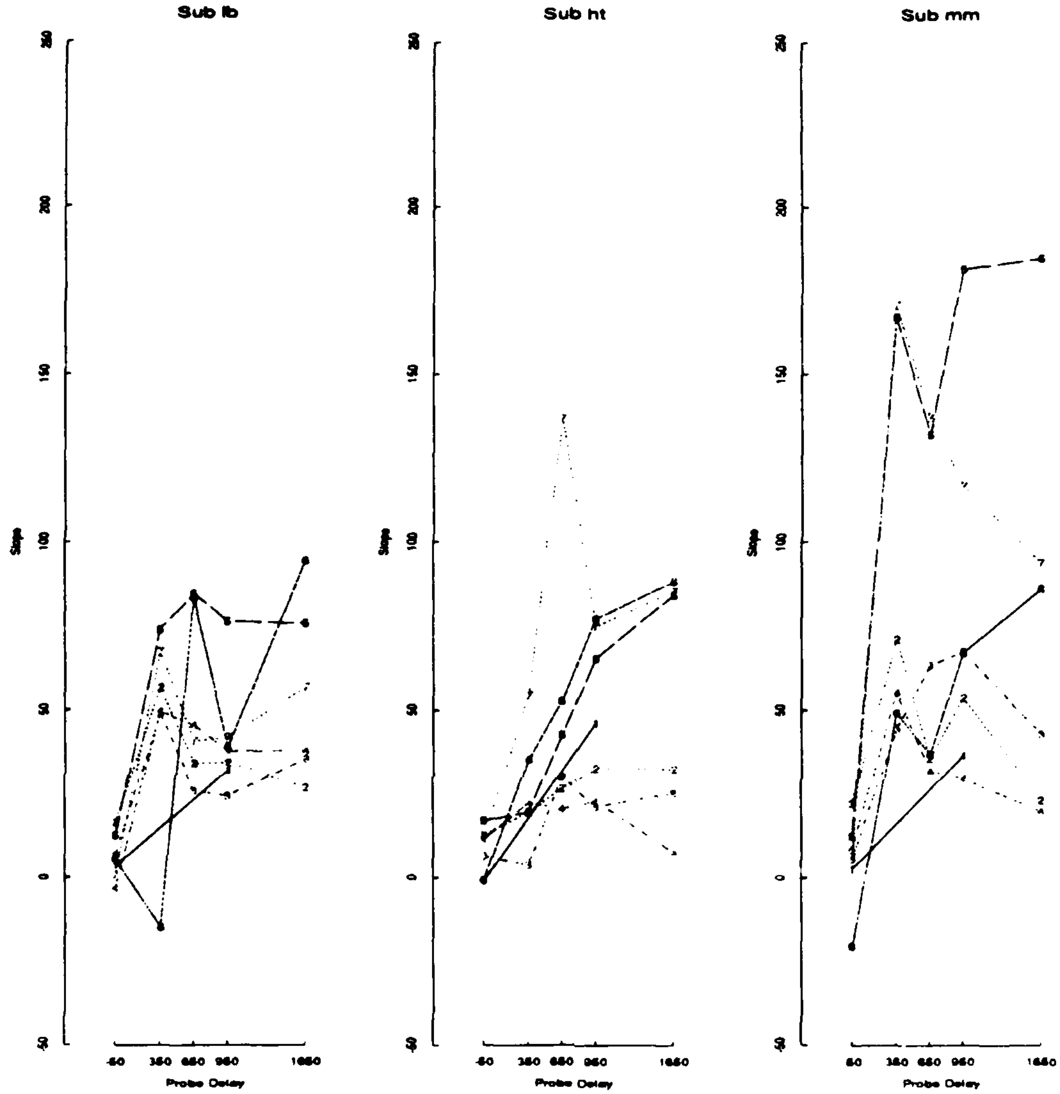
One reason for the lack of reliable changes in slope beyond the 350 ms probe delay may be the large between-subject slope differences present in the data. Figures 13 and 14 present plots of delay vs slope for individual subjects.

13. Actual slope values obtained by Sternberg & Knoll (1985) in the LP paradigm for the -50 and 950 probe delays were 4.6 and 72 ms/item, respectively (compared to the 3.1 and 39.6 ms/item obtained here); Sternberg, Knoll, & Turock (1985) obtained a value of 2.8 ms/item for the -50 probe delay.



1=LP; 2=MD(y); 3=MD(n/i); 4=MD(n/o); 5=MN(y); 6=MN(n/i); 7=MN(n/o).

Figure 13. Slope as a Function of Probe Delay for Subjects 1-3



1=LP; 2=MD(y); 3=MD(n/i); 4=MD(n/o); 5=MN(y); 6=MN(n/i); 7=MN(n/o).

Figure 14. Slope as a Function of Probe Delay for Subjects 4-6

It is evident from the figures (and from the standard error values in Table 4) that slope patterns are highly variable across subjects. Unfortunately, it also appears that no collection of data from a subset of subjects agree well enough to warrant investigation.[14] Consequently, while it is reasonable to conclude

14. Ideally, it would be desirable to determine whether the unevenness in the plots for individual subjects is due to large *within* subject variability. Unfortunately, such a measure is not readily computable from the data of the present experiment. Once each trial is classified by the independent variables in the experiment and error trials are omitted, there are generally only one or two observations in a cell. Other ways to approach the variability problem might be to either scale data for individual subjects by a single value such as the median slope computed over subjects, or scale the probe delay axis so as to achieve maximal similarity between subjects. Neither of these analyses were attempted because while they might lead to more agreement between subjects, it is not clear that the scaled result would be readily interpretable in terms of the experimental questions of interest.

that some transformation reliably occurs in all conditions, and that the nature of the transformation in the matching paradigms is similar to that observed in the LP paradigm for early delays, the progressive change in slope previously described by Sternberg et al. appears to be absent from the data of the present experiment.

3.6.8 Comparison of Response Conditions in MD and MN Paradigms

A central question addressed by this research concerns how the processing of forms with well-learned names differs from that of forms without well-learned names: any differences between the results from MD and MN paradigms would indicate differences in processing.

There are at least three candidates for a dependent measure in which to look for differences, the slope, intercept, and mean. The slope conveys information about the part of RT that is array-size dependent, i.e., the rate at which the representation is searched. Differences in slope between MD and MN paradigms would thus indicate that the search rate of the memory representations used in these paradigms differs, with larger slopes indicating slower search. The intercept measures the component of RT that is independent of array-size. Differences between the intercepts observed in the MD and MN paradigms would indicate that processes other than search, such as encoding the probe and generating the response, differ. The mean is a combination of slope and intercept. There are three difficulties associated with interpreting the mean, however. First, since the information it contains is a combination of the information in the slope and intercept, it is largely redundant. Second, the mean does not differentiate between processes that do and do not depend on array size. Consequently, it is less helpful in the analysis of underlying processing events. Third, in a situation where RT is known to vary with array size, the mean depends on the (arbitrary) choice of array sizes. Since different array sizes were used in the two paradigms, and since we know that larger array sizes lead to longer reaction times in long probe delay conditions, to correctly compute the mean we must compensate for these differences. Both slope and intercept measures compensate implicitly. For these reasons, the slope and intercept were chosen as the dependent variables to study; the mean was excluded.

Initial ANOVAs were performed on slopes and intercepts to uncover reliable patterns in the data. Factors in the ANOVA models are summarized in Table 9. In all analyses, the "subjects" factor was treated as a random effect; others were regarded as fixed effects.

Factor	Abbreviation	Levels
Matching paradigm	P	MD, MN
Response condition	C	yes, no/in, no/out
Probe delay	D	-50, 350, 650, 950, 1650
Subject	S	1, 2, 3, 4, 5, 6

Table 9. Summary of Factors in ANOVA Models

Analyses in which all factors were included indicated that response condition reliably interacts with delay and paradigm. To study the differences between results from the two paradigms in more detail, three separate ANOVAs were performed, one for each response condition. Factors in each of these ANOVAs included matching paradigm, probe delay, and subject. Table 10 presents a summary of the results of these analyses. Entries in the table include tests of both zero- and one-intercepts.[15]

15. The impetus for analyzing both intercepts is discussed in Section 3.6.5.

Response Condition	Factor	Dependent Variable	Mean Square	df	F	p
yes	P	Slope	28838.2	1,5	15.3	.01
		Zero-Int	29.4		0.0	.99
		One-Int	27025.6		9.5	.03
	D	Slope	4000.5	4,20	7.5	.001
		Zero-Int	19607.8		6.6	.001
		One-Int	7368.9		5.7	.003
	PxD	Slope	2229.6	4,20	4.3	.01
		Zero-Int	19642.4		4.2	.01
		One-Int	9289.3		3.6	.02
no/in	P	Slope	834.7	1,5	0.6	.47
		Zero-Int	97792.0		22.9	.005
		One-Int	116696.5		40.7	.001
	D	Slope	5391.0	4,20	19.4	<.001
		Zero-Int	39285.6		14.5	<.001
		One-Int	15789.5		10.5	<.001
	PxD	Slope	1146.0	4,20	2.2	.11
		Zero-Int	9510.9		2.1	.12
		One-Int	4207.6		2.0	.13
no/out	P	Slope	30754.6	1,5	14.8	.01
		Zero-Int	7246.0		0.9	.39
		One-Int	67857.3		11.5	.02
	D	Slope	10054.9	4,20	7.7	.001
		Zero-Int	53919.8		7.0	.001
		One-Int	19410.0		6.7	.001
	PxD	Slope	3801.6	4,20	2.8	.05
		Zero-Int	15195.9		2.3	.09
		One-Int	5703.2		2.6	.07

Table 10. Summary of ANOVAs Comparing MD and MN Paradigms

3.6.8.1 Slope Differences

Differences in slope revealed by this analysis are interesting because they indicate differences between the search rates of memory representations of forms with well-learned names and search rates of forms without them. The main effect of delay on slope has been considered before. Main effects of paradigm (P) on slope would indicate that one representation is searched at a slower rate than the other; paradigm by delay (PxD) interactions would indicate that the time course of the transformation differs for the two kinds of material. Using a p value of .05 as the criterion for significance, examination of the results indicate significant effects of both P and PxD on the slopes for yes and no/out trials. By combining this result with the information in Figure 9, it is evident that search rates are slower in these conditions for items without well-learned names and that the size of this slope difference varies with delay: For the MD(y) response condition, slopes rise between the -50 and 350 probe delays, then plateau after the 350 ms probe delay; for the MN(y) condition, slopes continue to rise until the 950 ms probe delay. For the MD(n/o) condition, slopes rise to a plateau at the 650 ms probe delay; for the MN(n/o) condition slopes rise to a peak at the 650 ms probe delay, then decline between probe delays of 650 and 1650 ms. Taken collectively, these findings indicate a basic difference in the time course of the transformations that occurs for named and nameless materials. The direction of these effects lead to two conjectures, either (1) the transformation for nameless forms takes longer, or (2) since nameless forms may be difficult to search once transformed, the underlying processing mechanisms maintain a concurrent representation that is spatially accessible as long as possible. Either of these conjectures might explain why slopes continue to grow in the yes response condition, and why the peak slope is shifted 300 ms to the right on the probe delay axis for no/out trials. A follow-up experiment in which more probe delays are studied (especially delays between -50 and 350 ms) should help to confirm or disconfirm these conjectures.

It is also interesting to note that neither the P or the PxD interaction is significant for the no/in condition. Examination of the plots in Figures 13 and 14 suggest one possible reason for this result: it is clear from the plots that there is minimal agreement between subjects in this condition.

3.6.8.2 Intercept Differences

Differences in intercept revealed by this analysis are important because they indicate differences in the time of processes not dependent on array size, such as encoding the probe and generating the response. The effect of probe delay on intercepts is analyzed in Section 3.6.12. Turning attention to the P and PxD effects, significant differences for P are noted for yes (one-intercept only), no/in, and no/out (one-intercept only) conditions. It is evident from Figure 9 that intercepts are greater in the MN paradigm at all delays, except for the yes response condition at the 1650 ms probe delay. (This reversal at 1650 ms leads to the PxD interaction in the yes response condition.) These results reveal that the time for processes independent of array size are reliably longer when materials consist of items without well-learned names.

3.6.9 Direct Access

In the context of the present work, *direct access* refers to a situation where no search or other time consuming process involving other display locations is needed to gain access to the probed location. The indicator of direct access in the present experiment is the slope of the latency function. Flat latency functions indicate direct access; functions with slope greater than zero indicate its absence.[16]

To determine which conditions of the present experiment produced direct access, *t*-tests were performed on the slope data from each combination of paradigm and response condition within each delay. Using a significance level of .05, the results of these tests indicated that delays greater than -50 ms resulted in slopes that were reliably greater than zero for all combinations of paradigm, probe delay, and response condition. Consequently, Table 11 summarizes the *t*-test results for the -50 delay only.

	Mean Slope Difference	SD	SE	t	p	df
LP	3.14	3.72	1.52	2.07	0.09	5
MD(y)	13.71	4.93	2.01	6.81	0.0	5
MD(n/i)	5.72	7.23	2.95	1.94	0.11	5
MD(n/o)	6.08	6.72	2.75	2.22	0.08	5
MN(y)	28.67	25.95	10.60	2.71	0.04	5
MN(n/i)	3.06	19.01	7.76	0.39	0.71	5
MN(n/o)	-4.25	16.54	6.75	-0.63	0.56	5

Table 11. Summary of *t*-tests for -50 Delay

16. Strictly speaking, direct access is indicated by values of slope that are exactly equal to zero. However, this stringent criterion ignores the (likely) possibility that small array-size effects might arise for other reasons such as the effect of context on legibility manifested through lateral interactions.

An analysis based solely on the significance level of a *t*-test relies on acceptance of the null hypothesis to determine the presence of direct access. This acceptance, however, is a necessary but not sufficient condition for concluding that direct access is present. For example, if three subjects' slopes were highly positive and three highly negative, the *t*-test would indicate a mean near zero, and a non-significant value of *t*. To assert the presence of direct access, examination of individual subjects' slopes is necessary. While the statistics in Table 11 suggest that direct access is present except in the yes response condition, values of subjects' slopes draw this interpretation into question. Table 12 presents slopes for the -50 probe delay by subject, paradigm, and response condition.

Subject	LP	MD(y)	MD(n/i)	MD(n/o)	MN(y)	MN(n/i)	MN(n/o)
jh	0.9	10.0	-6.7	2.8	21.0	-11.3	-26.8
cc	9.9	9.1	6.2	14.7	80.2	34.0	-23.3
jp	2.9	11.5	16.0	1.6	28.7	11.3	5.7
lb	3.5	16.5	6.7	-3.0	12.6	5.6	0.7
ht	-1.1	12.9	6.4	11.5	17.0	-0.7	11.9
mm	2.6	22.3	5.7	8.8	12.5	-20.5	6.4

Table 12. Slopes for -50 Delay by Subject

While there appears to be good agreement among subjects' data from the LP paradigm, it is evident that there is not as much agreement among subjects' slopes in the no/in and no/out conditions of the matching paradigms. Consequently, it appears to be reasonable to conclude only provisionally that direct access is present at the -50 ms delay for the no/in and no/out matching conditions. Clearly this conclusion needs to be confirmed with follow up research.

Data for the MD(y) and MN(y) conditions, with mean slopes 13.7 and 29.7 respectively, indicate that direct access is not present in these conditions, even at the -50 ms delay. This result is not explainable by large between-subjects variability: all subjects produced large and positive slope values. One possible explanation of this result that can be rejected on the basis of patterns in the data comes from subjects' introspections about the "yes" response trials. Some subjects reported using a rechecking strategy: after apprehending the probe, and concluding by an initial search that its identity matched that of the array item below it, they initiated a second search to verify that the probed item did not appear in any other location. Some subjects reported that this second search was through identity information, others that it was through location information, and others weren't sure. If subjects did employ such a strategy, at least two patterns in the data might be expected to emerge. First, the ratio of slopes on trials where subjects responded "yes" to the slopes on trials where subjects responded "no" should be approximately 2:1.[17] Examination of the values of slopes in Table 4 do confirm this expectation for the -50 ms delay, but not for any other delay in the experiment. Second, subjects' confidence ratings for "yes" responses might be expected to be higher (or lower) than for other trials, since their answer was rechecked. To assess this possibility, four *t*-tests were performed on the differences in confidence rating between yes and no response conditions in the -50 delay. The four dependent measures were computed as follows: MD(y) - MD(n/i), MD(y) - MD(n/o), MN(y) - MN(n/i), and MN(y) - MN(n/o). If subjects were reliably more confident of "yes" responses, the mean differences would be positive; if they were less confident, differences would be negative. Table 13 presents the results of this analysis.

17. This prediction relies on two assumptions: (1) Rechecking is done on every trial, and (2) the state of the representation is the same for every trial in a given delay.

	MD(y)–MD(n/i)	MD(y)–MD(n/o)	MN(y)–MN(n/i)	MN(y)–MN(n/o)
Mean	-0.0028	0.0001	0.0172	-0.0282
SD	0.0046	0.0038	0.0259	0.0441
SE	0.0019	0.0016	0.0106	0.0180
t	-1.46	0.09	1.62	-1.57
p	0.20	0.93	0.17	0.18
df	5	5	5	5

Table 13. Summary of *t*-tests on Confidence Ratings for -50 Probe Delay

It is evident that mean differences in confidence are very small and not in a consistent direction.

Subject	Difference in Confidence			
	MD(y)–MD(n/i)	MD(y)–MD(n/o)	MN(y)–MN(n/i)	MN(y)–MN(n/o)
jh	-0.0056	-0.0056	0.0184	-0.0255
cc	0.0	0.0	-0.0031	-0.1163
jp	0.0	0.0	0.0441	0.0
lb	0.0	0.0	-0.0042	-0.0069
ht	0.0	0.0	-0.0050	-0.0050
mm	-0.0111	0.0064	0.0529	-0.0157

Table 14. Mean Confidence Differences for the -50 Probe Delay by Subject

It is also evident from the standard errors in Table 13 and the difference values for individuals in Table 14 that the large values of p observed are not simply a consequence of excessive between-subject variability.

To summarize, unless the (somewhat questionable) assertion is made that a second search process was initiated only in the yes response condition at the -50 ms probe delay, the results of these tests do not seem to be consistent with the strategy given in subjects' introspective reports; the reason for the large slopes observed in "yes" response condition remains unexplained. This suggests that a follow up study designed to address the "yes" versus "no" response differences may be useful. In the present study, the strategy subjects reported relied on the fact that on "yes" trials only one element in the array was identical to the probe. One way to prevent subjects from using such a strategy, and at the same time assess other interesting issues (e.g., the selectivity question), would be to include one or more out-of-location probes as well as an in-location probe in arrays on "yes" trials.

Beyond the -50 probe delay, the large and reliable slopes indicate that the direct access property is absent. This finding adds further credence to results from the Sternberg et al. work with the LP paradigm, and provides further evidence against the assumption often made in studies of visual display processing that the direct access property is present at all delays.

3.6.10 Selective Access

As previously discussed, *selective access* describes situations in which direct access may or may not be present, but the *contents* of display locations other than the one probed are not processed in any way. Selective access is violated when, with non-zero probability, the contents of locations other than the one probed influence the processing required to find and respond to the probed item. In the present context, if a representation is selectively accessed, then elements that have the same identity as the probe, but are not in the probed location should neither facilitate or impede a "no" response. That is, selectivity is demonstrated if data from no/in and no/out trials are identical. Non-selectivity is demonstrated by any differences between the two types of trials.

In the context of the present work, the parametric indicators of selectivity are the slope and intercept. Non-selectivity is revealed by reliable differences in one or both measures. In addition to providing an indicator of whether selectivity is present or absent, the patterns of change in these measures also reveal something about the *kind* of effect that non-selectivity has on processing. If differences appear in slopes, this suggests that non-selectivity causes changes in search speed. Differences in intercept (not accompanied by concomitant changes in slope), imply the effect of non-selectivity is on something unrelated to the search process *per se*, such as response generation time.

The selectivity issue was addressed with two analyses. First, an analysis of variance with factors subject (1-6), probe delay (-50, 350, 650, 950, 1650), paradigm (MD, MN), and response condition (no/in, no/out) was performed on slopes. All interaction terms were reliable, $p < .05$. Consequently, in the second analysis data were divided into smaller units to determine which conditions led to selectivity and which did not. In the second analysis, the difference between slope values in the no/in and no/out response conditions was computed for each combination of subject, matching paradigm (MD, MN), and probe delay. This operation was repeated for intercept values. To test for the presence of selectivity, t-tests were performed on these differences. Table 15 summarizes the outcome of this analysis. Rows of the table represent paradigms and, within each paradigm, the parameter that was tested. Columns of the table correspond to probe delays. Entries in the table are mean differences (no/in – no/out) between parameter values averaged over subjects and the standard errors of these differences. To the right of the mean difference and enclosed in parenthesis is one of two letters, a "p" if the data in this cell suggested selectivity was present and an "a" if selectivity was absent. The presence/absence judgment was made by performing a 5 df t-test under the null hypothesis of population mean equal to zero, and the alternative hypothesis of mean greater than zero. A .05 level of significance was used as the criterion for rejecting the null hypothesis.

		Probe delay (ms)				
Paradigm	Parameter	-50	350	650	950	1650
	Slope	-0.4(p)	-12.1(a)	7.6(p)	19.7(p)	15.0(p)
	SE	4.1	3.4	6.7	9.2	6.1
	Zero-Int	13.4(p)	73.2(a)	9.1(p)	5.6(p)	-8.0(p)
MD	SE	13.1	17.9	22.5	16.5	18.9
	One-Int	13.0(p)	61.0(a)	16.7(p)	5.6(p)	7.0(p)
	SE	9.5	15.2	16.6	16.5	13.7
Conclusion		p	a	p	p	p
	Slope	7.3(p)	-58.6(p)	-71.5(a)	-51.0(p)	14.4(p)
	SE	11.7	26.7	26.4	36.2	9.1
	Zero-Int	11.3(p)	89.13(p)	144.6(a)	140.9(p)	-18.6(p)
MN	SE	38.5	59.5	46.1	85.9	22.8
	One-Int	18.6(p)	30.6(p)	73.1(a)	90.0(p)	-4.2(p)
	SE	27.3	37.5	27.4	50.5	16.6
Conclusion		p	p	a	p	p

Table 15. Mean Differences Between No/in and No/out Response Conditions

The analyses suggest that selective access is present in nearly all of the combinations of paradigm and probe delay. The four exceptions are for the slope and intercept in the MD paradigm at the 350 ms probe delay, and for the slope and intercept in the MN paradigm at the 650 ms probe delay. This suggests that there may be an intermediate state in which selectivity disappears, then reappears as the transformation is completed. The fact that this difference occurs later in the MN paradigm may also indicate that the transformation for items with well-learned names is delayed relative to the transformation that occurs for the MD paradigm, or that the assimilation of the probe takes longer in the

MN condition so that the transformation is further advanced. However both of these conjectures are highly speculative since, analogous to the previous section, accepting the null hypothesis is a necessary but not sufficient condition for concluding the presence of selectivity. Examination of the standard error values and the slope and intercept values for individual subjects reveals that many of the non-significant t's may be a consequence of large between-subjects variability, rather than a consistently low difference.

To summarize, the representations in both MD and MN paradigms appear to dynamically change with increasing probe delay in such a way that selectivity is present, then absent, then present again. Clearly this conclusion needs to be confirmed with follow up research. If it is borne out by such research, it will demonstrate yet another dimension in which STVM is dynamic rather than simply fading, as many researchers have proposed. It will also suggest that selectivity *is* possible when items are less than one degree of visual angle apart, in contrast to several earlier findings.

3.6.11 Effect of Response Ensemble

Another important issue addressed by this research is whether the effects observed by Sternberg et al. in the LP paradigm could be due to a confounding between array size and the number of possible responses. With short probe delays subjects may not have time to selectively prepare for the set of possible responses; with longer delays they may have time to prime some responses, since they know the probed item will have to be among those in the array, and discard others. Consequently, as probe delay increases, responses for arrays with fewer items could be facilitated relative to responses for larger arrays. If the effects observed in the LP studies of Sternberg et al. or the present experiment could be explained by this "response ensemble" interpretation, no slope changes should be manifested in either of the matching paradigms, since the number of response alternatives in these paradigms is always two, regardless of array size. The fact that slopes do increase and, in the case of the MD paradigm, are similar to those found in the LP paradigm indicates that the response ensemble interpretation is not tenable.

3.6.12 Analysis of Intercepts

The question that relies primarily on the intercept as a dependent measure concerns Sternberg & Knoll's (1985) conjectured association between changes in intercept and the availability of names. According to Sternberg & Knoll, as the transformation progresses, the internal representation of an item changes in such a way that once the representation is retrieved, its associated name can be derived from it more rapidly. By this hypothesis, the time to determine the name of an item depends on the state of the representation. If the item is only partially transformed, more processing is required to generate its name. As the state of the representation becomes more transformed, the processing time required decreases.

Tests of this conjecture are possible with the data from the present experiment. For example, we can determine if the decrease in intercept with increasing probe delay observed in the Sternberg, et al. experiments is observed here. The matching paradigms also allow additional tests of the conjecture, since they do not *require* a naming response. If a reliable decrease in intercept failed to be observed in either matching paradigm, this would support the conjecture. If a reliable decrease was observed, it would not falsify the conjecture however, since the MD and MN paradigms do not *guarantee* that subjects do not generate names for items, or that there is no other process that brings the representation close to the response.

To address these questions, it is desirable to compare intercepts at the shortest and longest delays. However, values of intercepts at these delays may not be readily comparable. Consider the two possible relations between the onset of the array and probe, and the beginning measurement of RT depicted in Figure 15.

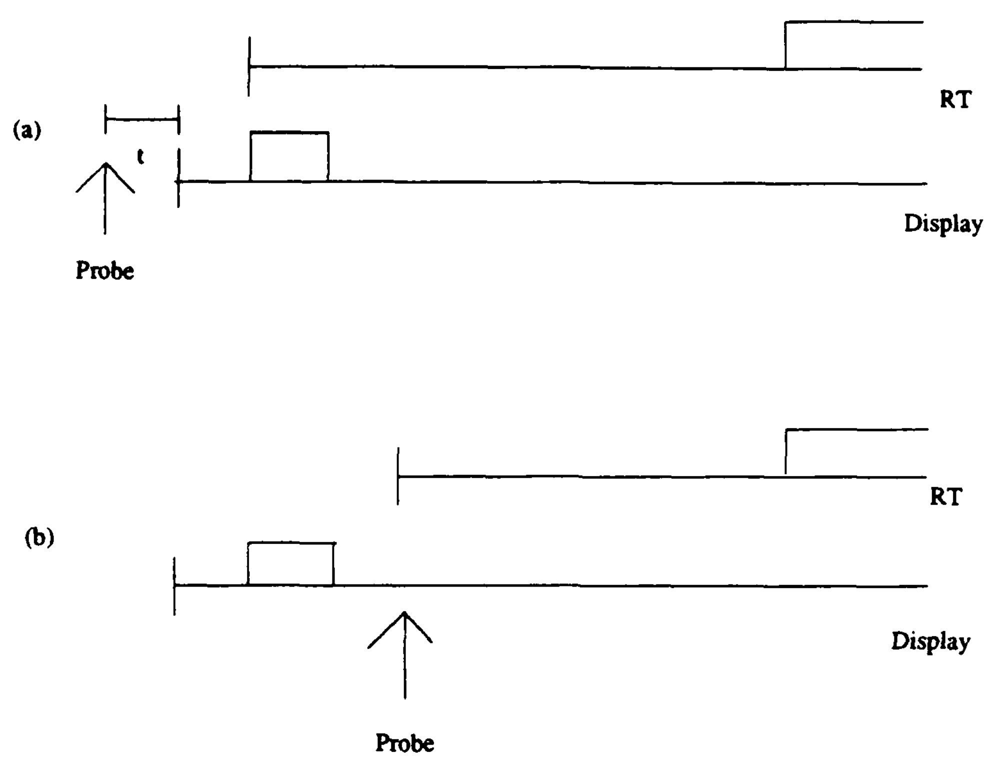


Figure 15. Time Relations Between Probe and Array

In case one, the probe (represented by the arrow) comes on before the array, and t ms before the RT clock starts. In case two, the probe appears some time after the array has disappeared. Adjustments to RT may be indicated, depending on whether the probe and array processing is serial, parallel, or multiplexed. If the probe and array processing is serial, then the probe processing time (up to t) is excluded from RT in case one. Consequently, to make the intercept at the -50 ms probe delay comparable to those obtained at later delays, 50 ms must be added to RT for the -50 delay trials.[18] If the probe and array processing are fully parallel, then the probe processing time is never included in RT. Thus, no change is necessary. Finally, if the probe and array processing are multiplexed with some overhead incurred for switching between processing one and then the other, some quantity more than t must be added to RT.

It is assumed that the time that would be added to RT is time that is not affected by processes dependent on the number of items in the array. Consequently, adding this time will result in an increased intercept value, rather than one that decreases or stays constant. Since the data of the present experiment do not provide a way to differentiate between the three models, a conservative approach is to begin by not adjusting the -50 ms probe delay intercept, and performing comparisons to determine if a reliable drop in intercept occurs. If a significant drop is noted, then it is obvious that adding a constant (50 ms) to the intercept for the -50 ms probe delay will only *increase* the magnitude of the difference, and hence the level of significance. If the change is determined not to be significant, then the next course of action becomes problematic.

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18. This assumes, of course, that t is less than the probe processing time.

To quantitatively address the intercept question, t-tests were performed with the null hypothesis that the value of the appropriate intercept at the longest delay subtracted from the value of the analogous intercept at the -50 delay was equal to zero. Thus, for the LP paradigm, the -50 and 950 delays were compared: for the matching paradigms the -50 and 1650 delays were used. In all cases except MD(n/o) and MN(n/o), the one-intercept was the dependent variable. For these two conditions, both zero- and one-intercepts were compared. Table 16 summarizes the results of the tests.

Condition	Intercept	Mean Difference	SD	SE	t	p	df
LP	One	76.50	30.03	12.26	6.24	0.0	5
MD(y)	Zero	13.32	37.69	15.39	0.87	0.43	5
MD(y)	One	0.28	28.87	11.78	0.02	0.98	5
MD(n/i)	Zero	81.99	17.47	7.13	11.50	0.0	5
MD(n/i)	One	48.74	14.11	5.76	8.46	0.0	5
MD(n/o)	Zero	60.64	53.82	21.97	2.76	0.04	5
MD(n/o)	One	42.77	40.77	16.65	2.57	0.05	5
MN(y)	Zero	175.94	133.85	54.65	3.22	0.02	5
MN(y)	One	104.32	82.26	33.58	3.11	0.03	5
MN(n/i)	Zero	205.94	92.93	37.94	5.43	0.0	5
MN(n/i)	One	127.97	65.98	26.94	4.75	0.01	5
MN(n/o)	Zero	176.03	72.62	29.65	5.94	0.0	5
MN(n/o)	One	105.12	51.12	20.87	5.04	0.0	5

Table 16. Results of t-tests on Intercept Differences

These tests reveal a reliable drop in intercept for all conditions, except MD(y). Examination of the individual differences in intercepts for this condition suggests an explanation for why this value of t is small: differences for the six subjects in this condition are -17.5, 15.8, 68.3, 6.5, 41.4, and -34.5 for the zero-intercept; -12.1, -14.0, 45.4, -4.1, 21.9, and -35.5 for the one-intercept, respectively.

The results of this analysis do not provide evidence in favor of the conjectured association between intercepts and availability of names. Instead these results suggest that either items were covertly named in all conditions or that the conjectured association between decline in intercept and naming is incorrect. Unfortunately, the conditions and data of the present experiment do not provide a test to discriminate among these alternatives.

3.6.13 Feature vs Name Matching Hypothesis

The inclusion of trials with array size equal to one ("s=1 trials") in the design of the present experiment allows a test of the Posner et al. (1967) hypothesis that when stimuli are physically identical, short intervals between stimulus onsets allow rapid comparison between visual representations, but after some delay this visual representation is transformed into one based on a name code, and these codes are compared. If the Posner et al. interpretation is correct, RT for stimuli with well-learned names should increase with increases in probe delay, while RT for stimuli without well-learned names should remain the same.

To express regression coefficients for s=1 trials as fitted reaction time measures, the value of the mean term (μ) from the robust regression was added to each estimated value of α_1. Table 17 presents the mean values of these fitted times averaged over subjects along with their associated standard errors.

Paradigm/ Condition		Probe Delay (ms) -50	350	650	950	1650
LP	Mean	456.1			441.5	
	SE	17.0			19.1	
MD(y)	Mean	542.7	584.1	559.0	551.1	569.9
	SE	20.3	29.9	19.6	25.2	23.5
MD(n/o)	Mean	570.9	578.2	571.6	543.4	565.4
	SE	19.9	23.0	20.8	20.2	24.6
MN(y)	Mean	621.8	677.0	650.6	664.3	645.3
	SE	32.2	43.7	45.4	44.6	34.7
MN(n/o)	Mean	639.5	726.6	708.0	679.8	652.6
	SE	27.8	47.8	56.0	40.0	33.9

Table 17. Mean Fitted RT and Standard Error of RT for s=1 Trials by Probe Delay and Condition

To assess the validity of the name vs feature matching hypothesis, an ANOVA with factors subject (1-6), probe delay (-50, 350, 650, 950, 1650), matching paradigm (MD, MN), and response condition (yes, no/out), was performed. If the feature vs name match hypothesis is correct, a reliable interaction of paradigm and delay would be expected. The ANOVA confirmed this expectation, $F(4,20) = 3.4$, $p < .028$. Significant effects of response $F(1,5) = 24.1$, $p < .004$, and probe delay $F(4,20) = 7.6$, $p < .001$, were also present. However, the pattern of the effects are not as expected. To allow the reader to study these effects in detail, Figure 17 shows mean values of fitted RT for s=1 trials by paradigm, response condition, and probe delay. Curves in the figure correspond to the four conditions 1 = MD(y), 2 = MD(n/o), 3 = MN(y), 4 = MN(n/o).

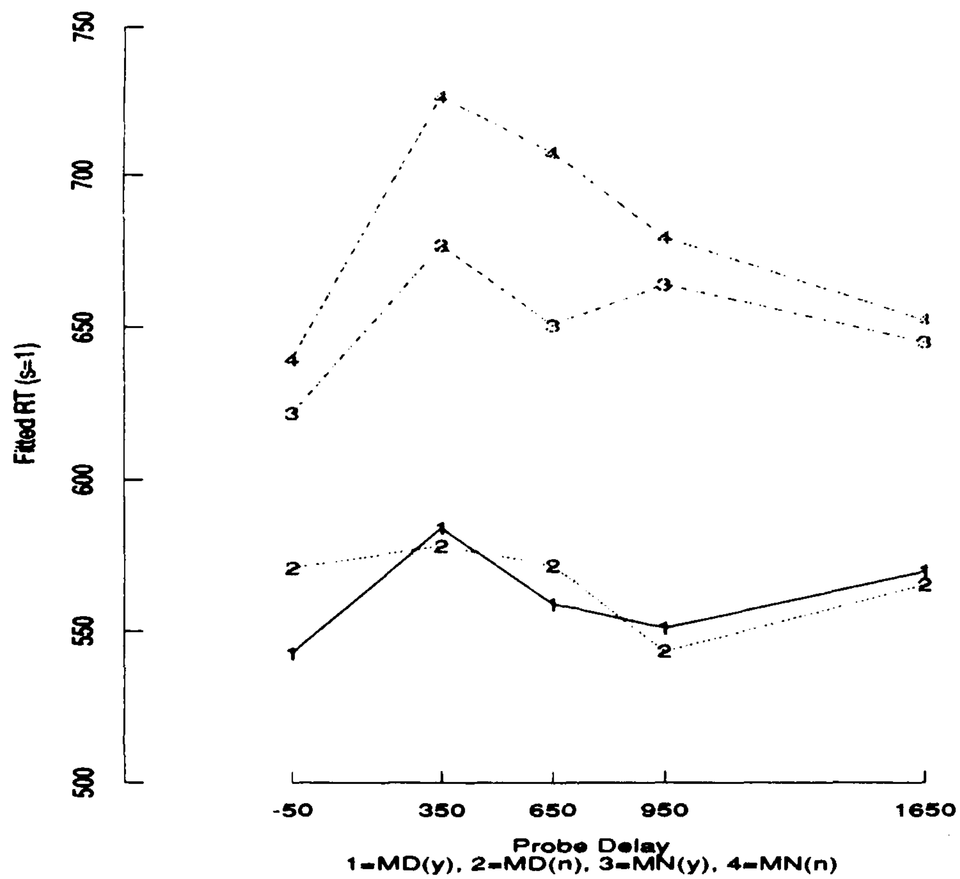

Figure 16. Mean Fitted RT for s=1 Trials by Probe Delay

4. Summary and Conclusions

A review of the literature on short-term visual memory (STVM) revealed a great deal of uncertainty and controversy about the mechanisms of processing that underly performance when a row of letters or digits is presented and a person attempts to identify and remember the characters it contains. It was evident that in much of the research on STVM two assumptions are made: (1) for all probe delays a spatially contiguous subset of one or more of the items in memory can be accessed without search through other items, and (2) the memory representation that is accessed is analogous to a "fading photograph" and is not actively changed by cognitive processing. Results from recent experiments by Sternberg et al. and others suggested that these assumptions were incorrect by demonstrating that (1) under certain circumstances STVM *must* be actively searched, and (2) STVM undergoes an active transformation, rather than passively decaying.

In the latter experiments displayed material was restricted to alphanumeric items with well-learned names, and a naming response was required. The primary focus of the present research was to determine to what extent the processing underlying performance in STVM tasks depends on displayed material having well-learned associations with names. A new experimental paradigm was developed that did not require items in memory to have names or be named. Because naming is not required, the new paradigm allowed several important questions about the mechanisms of visual information processing to be investigated, as well as providing a test of the generality of some of the results of Sternberg et al.

Data were collected in a large (75,000 trial) experiment to address these questions. A multiple regression model was created and applied to the data to compensate for non-orthogonality in experimental factors that could not be avoided. Several models of the processing mechanisms underlying performance were proposed. While some of the models did better than others, none were able to completely account for the patterns observed in the data. These results of the model building efforts did provide guidance in choosing a measure of the components of RT that did not depend on array-size, however.

The results of the multiple regression were then considered to answer several research questions. A summary of these questions, and the conclusions drawn, comprises the remainder of this section.

4.1 Linearity of Latency Functions

What is the relationship between the number of items presented and the time to either name a marked item, or determine whether an item matched the item immediately below it? In the earlier work of Sternberg, et al., the relationship between reaction time and array size was found to be approximately linear for all probe delays. This finding was replicated in the present research. Tests of the presence of non-linear terms indicated the presence of small quadratic and (where a test was possible) cubic components neither of which interacted with any of the experimental conditions of interest.

4.2 Evidence for a Transformation

Is the underlying memory representation actively processed and dynamically changing as Sternberg et al. hypothesize, or does it simply "fade" as many researchers have assumed? In all paradigms, changes in the slopes of latency functions with increases in probe delay indicated that the memory representation is actively processed and undergoes a rapid transformation from a state in which items stored in it are accessible by spatial location to a second state that requires serial search.

4.3 Detailed Analysis of the Transformation

Given the presence of a transformation, how are the transformations that occur in each paradigm similar and how they are different? To study this issue, detailed analyses of the slopes of the latency functions in each paradigm were performed. The pattern of the transformation evidenced in the naming paradigm both here and in the earlier work of Sternberg et al. was determined to be similar to that observed in the matching paradigms of the present experiment. Slopes from the naming paradigm were approximately zero for negative and small positive probe delays, and rose as delay was increased, reaching asymptote by approximately 3/4 second. Three patterns emerged in the matching data from this experiment: (1) Some slopes were initially near zero, and reached asymptote earlier than in previous work with the naming paradigm — by the 350 ms delay; (2) Some slopes were initially zero, rose to a peak at the 350 ms delay, then declined for longer delays; (3) Some slopes were reliably greater than zero even at the -50 delay, and rose to asymptote by the 350 ms delay. Since asymptote appears to be reached by the 350 ms probe delay, analysis of the time course of the transformation for matching paradigms (paralleling the time course analyses of Sternberg et al.) was inconclusive. This suggests that another study needs to be performed in which probe delays between -50 and 350 ms are studied for the matching paradigms.

4.4 Comparison of MD and MN Response Conditions

How does the processing of forms with well-learned names differ from that of forms without well-learned names? Differences between slopes indicated that search rates are significantly slower for nameless items and that the size of this slope difference varies with delay. Differences between intercepts indicated that the time for processes independent of array size (such as the time to encode the probe and generate the response) are also reliably longer when materials consist of items without well-learned names.

4.5 Direct Access

Direct access refers to a situation where no search or other time consuming process involving display locations is needed to gain access to a specified display location. Is direct access present in the matching paradigms? The indicator of direct access is the slope of the latency function. Flat functions indicate direct access; functions with slope greater than zero indicate its absence. The flatness of latency functions for the -50 ms probe delay in the naming paradigm and in the "no" response trials of the matching paradigms suggested the presence of direct access, however, large between-subject differences prevent making this assertion with certainty. The large slopes for the -50 ms probe delay for the "yes" response trials of the matching paradigms suggests the absence of direct access. It was hypothesized that this finding might be due to subjects use of a rechecking strategy, but no quantitative evidence in support of this hypothesis was found. The rapid increase of slopes with probe delay indicates that direct access is not present for probe delays longer than -50 ms in any of the three paradigms.

4.6 Selective Access

Selective access describes a situation in which direct access may or may not be present, but the content of display locations other than the one probed is not processed. Is selectivity achieved in any of the experimental conditions? Slope and intercept patterns suggested that selectivity was present for short probe delays, absent for an intermediate delay, and then present for very long delays.

4.7 Response Ensemble Interpretation

Could the effects observed by Sternberg et al. in the naming paradigm be due to a confounding between array size and the number of possible responses? If the effects observed in the naming conditions of Sternberg et al. or the present experiment were due to this response ensemble effect, no slope changes should have been manifested in either of the matching paradigms, since the number of response alternatives in these paradigms is always two, regardless of array size. The fact that slopes do change with increases in probe delay indicates that an explanation of the search phenomena based on increasing adaptation to the number of possible responses is not tenable.

4.8 Association between Intercept Changes and Naming of Items

Is Sternberg & Knoll's (1975) conjectured association between changes in intercept and the availability of names correct? According to Sternberg & Knoll, as the transformation progresses the internal representation of an item changes in such a way that once it is retrieved, the item's name can be derived from the representation more rapidly. Since items in the matching paradigms need not necessarily be named, it was hypothesized that failure to observe significant decreases in intercept would provide evidence supporting the Sternberg et al. conjecture. Reliable decreases in intercept were found in all conditions. Consequently, it was concluded that either items were covertly named in all conditions of the present experiment, or that the conjectured association between decline in intercept and the availability of names is incorrect.

4.9 Feature vs Name Matching Hypothesis

Are the conclusions from the Posner, Boies, Eichelman, & Taylor (1967) name vs feature matching study supported by data from the Location-Specific Matching Paradigm? The inclusion of trials with array size equal to one allowed a test of a property suggested by the Posner et al. (1967) work in which short probe delays lead to comparison between visual representations while long delays lead to comparisons between name-based codes. It was hypothesized that if the Posner et al. interpretation was correct, RT in the matching paradigm for stimuli with well-learned names should increase with increases in probe delay, while RT for stimuli without well-learned names should remain the same. Patterns in the data of the present experiment were inconsistent with the expectations based on the Posner model: RT for stimuli with well-learned names changed only slightly compared to the large change evidenced for stimuli without well-learned names.

5. Future Research

Most of the questions addressed by the present study had clear answers. The results also led to many new questions for future research. Some interesting questions for investigation in future experiments are now briefly discussed.

In the present experiment slopes were near zero in most conditions at the -50 probe delay, increased to much larger values at the 350 probe delay, and did not reliably increase after that. A follow up experiment in which data are collected at probe delays between -50 and 350 ms is thus desirable.

The data showed considerable between subjects variability. One of the reasons for this variability may have been that subjects learned certain contingencies in the experimental design, and adopted response strategies such as rechecking responses, or using the knowledge that when an element with the same identity as the probe was found in a non-probed location they could immediately respond "no" without checking the probed location. One solution, which eliminates the use of this strategy, is to include out-of-location probe items on yes as well as no/in trials, and to include more than one out-of-location target on some proportion of the trials.

Another potential source of the variability observed is that subjects ignored instructions to maintain eye fixation throughout each trial. However, a follow-up experiment in which conditions where eye fixation was measured and controlled were compared with conditions where it was not, suggested that eye movements were not a significant contributor to variability. This finding needs to be confirmed in a larger and more carefully controlled study.

Finally, in the present experiment selectivity was determined to vary with delay. In the experiment, out-of-location targets were always adjacent to the probed location. An experiment in which the position of out-of-location targets relative to the probed location is systematically manipulated and studied might provide further insight into the effects of selectivity. For example, one interesting question is whether selectivity is affected by the distance between probed location and the location containing a matching item, or whether the mere *presence* of an out-of-location target influences the search process.

Appendix 1: Regression Design Matrix for LP and MD Paradigms

0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	1	0	0	-1	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	0	0
0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	1	0	0	-1	-1	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	1	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-1	-1
0	0	1	0	0	-1	-1	0	0	0	0	0	0	0	-1	-1	-1	-1	0	0
0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
0	0	0	1	0	0	0	-1	-1	-1	0	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	-1	-1
0	0	0	1	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	1	0	0
-1	-1	-1	-1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
-1	-1	-1	-1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
-1	-1	-1	-1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	-1	-1
-1	-1	-1	-1	0	0	0	0	0	0	-1	-1	-1	-1	0	1	0	0	0	0
1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
1	0	0	0	1	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	0	0

Appendix 2: Regression Design Matrix for MN Task

0	1	0	1	0	0	0	0	0	1	0	0	0
0	1	0	-1	0	0	0	0	0	0	1	0	0
0	1	0	1	0	0	0	0	0	0	1	0	0
0	1	0	-1	0	0	0	0	0	0	0	1	0
0	1	0	1	0	0	0	0	0	0	0	1	0
0	1	0	-1	0	0	0	0	0	-1	-1	-1	0
0	0	1	0	1	0	0	0	0	1	0	0	0
0	0	1	0	0	1	0	0	0	0	0	0	1
0	0	1	0	-1	-1	0	0	0	0	0	1	0
0	0	1	0	1	0	0	0	0	0	1	0	0
0	0	1	0	0	1	0	0	0	0	0	-1	-1
0	0	1	0	-1	-1	0	0	0	-1	-1	-1	0
-1	-1	-1	0	0	0	1	0	0	1	0	0	0
-1	-1	-1	0	0	0	0	1	0	0	0	0	1
-1	-1	-1	0	0	0	0	0	1	0	0	-1	-1
-1	-1	-1	0	0	0	-1	-1	-1	0	1	0	0
1	0	0	1	0	0	0	0	0	1	0	0	0
1	0	0	1	0	0	0	0	0	0	1	0	0
1	0	0	1	0	0	0	0	0	0	0	1	0
1	0	0	1	0	0	0	0	0	-1	-1	-1	0

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